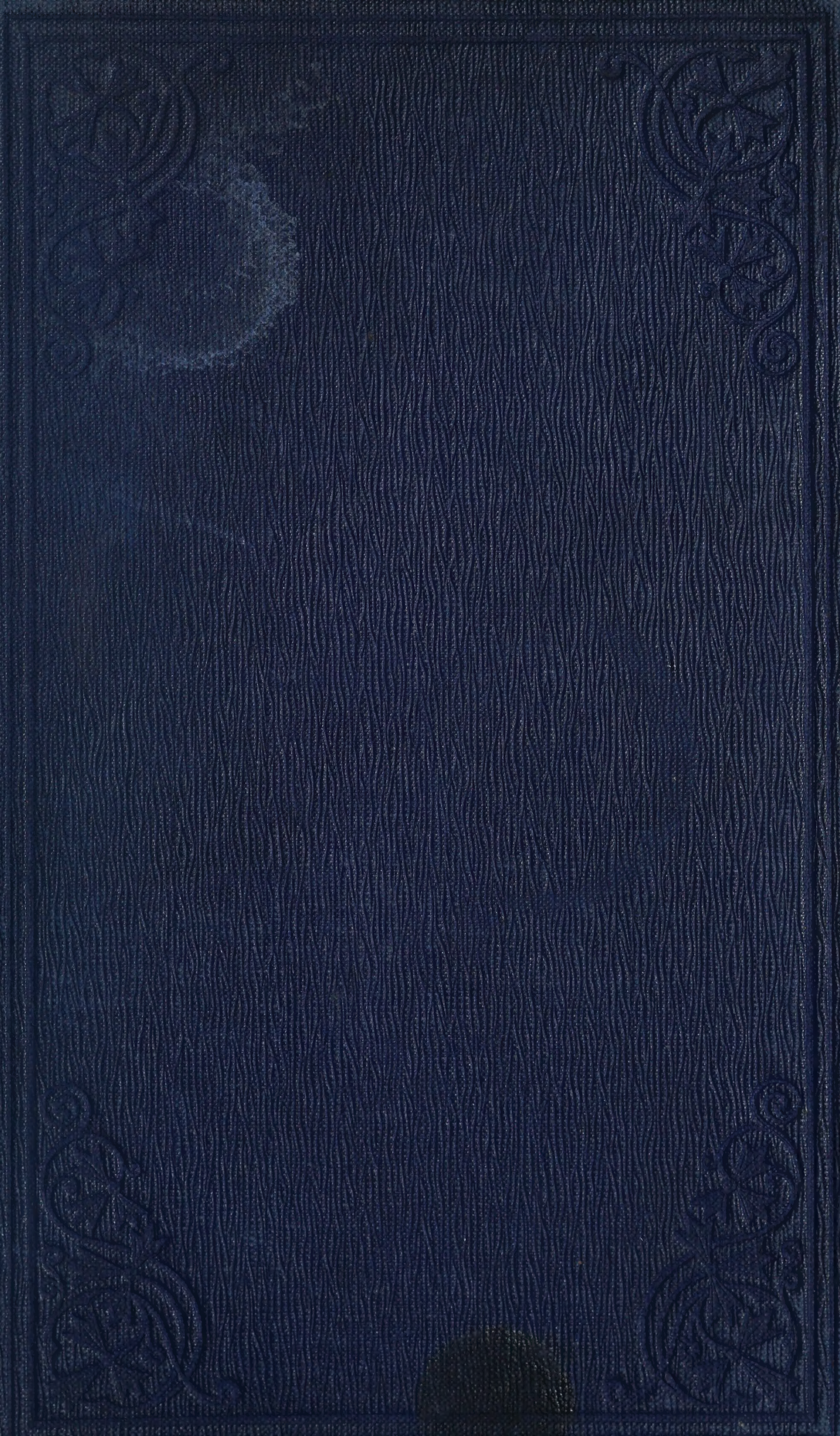


Now, as of old,
  Man by himself is priced.
For thirty pieces Judas sold
  Himself, not Christ. *Cholmondeley.*

Frederic E. Storey

-H.M.S. Arlanza 1915-1919.

10361

To. F. L. Higginson Jr.
October 1930:

Acc. #14,370
Library of
PEABODY MUSEUM · SALEM · MASSACHUSETTS · 1799 · 1867
ETHNOLOGY — NATURAL HISTORY — MARINE
Gift of
F.L. Higginson, Jr.

Supplied for the Public Service.

M. 21918/14. [*Crown Copyright Reserved.*

ADMIRALTY MANUAL

OF

NAVIGATION.

Admiralty Manual of Navigation, 1914.

ERRATA.

Art. 33. Chart facing page 36 should be numbered Fig. 23.

Art. 240, *line 5, Delete words* "signifying morning and afternoon."

LONDON:
PRINTED UNDER THE AUTHORITY OF HIS MAJESTY'S
STATIONERY OFFICE
BY EYRE AND SPOTTISWOODE, LTD., EAST HARDING STREET, E.C.,
PRINTERS TO THE KING'S MOST EXCELLENT MAJESTY.

To be purchased, either directly or through any Bookseller, from
WYMAN AND SONS, LTD., 29, BREAMS BUILDINGS, FETTER LANE, E.C., and
54, ST. MARY STREET, CARDIFF; or
H.M. STATIONERY OFFICE (SCOTTISH BRANCH), 23, FORTH STREET, EDINBURGH; or
E. PONSONBY, LTD., 116, GRAFTON STREET, DUBLIN;
or from the Agencies in the British Colonies and Dependencies,
the United States of America, the Continent of Europe and Abroad of
T. FISHER UNWIN, LONDON, W.C.

1915.

Price Three Shillings.

1031.1
G786
1915

The Lords Commissioners of the Admiralty have decided that a Standard Work on Navigation is required for the information and guidance of the Officers of His Majesty's Fleet; for this purpose the "Admiralty Manual of Navigation" has been compiled by Commander Henry E. F. Aylmer and Naval Instructor John White, M.A., under the supervision of the Director of Navigation.

The Manual is designed to supply the needs of Junior Officers and also of Officers qualifying for the duties of Navigating Officer, and is to be regarded as the Standard Work on Navigational questions in His Majesty's Fleet.

By the publication of this Manual the following books are superseded and may be destroyed:—

Notes bearing on the Navigation of H.M. Ships.

Handbook of Pilotage.

By Command of Their Lordships,

W Graham Greene

ADMIRALTY, S.W.
December 1914.

/66

u (12)17415 Wt 363—P 220 12,500 2/15 E & S

PREFACE.

The Admiralty Manual of Navigation consists of four parts :—

Part I. deals with the rhumb line and the position line, as well as with finding the error of the chronometer and the times of rising and setting of heavenly bodies ;

Part II. deals with pilotage ;

Part III. deals with the movements of the atmosphere and ocean ;

Part IV. gives descriptions of the various navigational instruments, and explains how their errors are eliminated or allowed for.

Thanks are due to—

The Astronomer Royal,
The Director of the Meteorological Office, for their valuable assistance,

and to

W. G. Perrin, Esq.,

for reading the proofs of the book. The method of keeping the reckoning during manœuvres is the work of Lieutenant-Commander L. H. Shore, R.N.

Figs. 262 and 263 have been reproduced from "Les Nouvelles Méthodes de Navigation" by A. Ledieu, and the permission which has been granted by—

Messrs. Elliot Stock to reproduce Fig. 153,
,, Elliott Bros. ,, ,, Figs. 240, 251, 252, 253,
The Sperry Gyroscope Co. to reproduce Figs. 247, 248,
Messrs. Cary, Porter & Co. ,, ,, Fig. 256,

is gratefully acknowledged.

The following books have been consulted :—

American Practical Navigator.	Nathaniel Bowditch, LL.D.
Cours de Navigation -	E. du Bois.
Descriptive Meteorology -	W. L. Moore, LL.D., Sc.D.
Deviations of the Compass in Iron Ships.	Captain E. W. Creak, C.B., F.R.S., R.N.
Elementary Meteorology -	R. H. Scott, M.A., F.R.S.
Encyclopædia Britannica.	
Etude sur les Courbes de hauteur.	G. Hilleret.
Ganot's Physics - -	E. Atkinson, Ph.D., F.C.S. A. W. Reinold, M.A., F.R.S.

Geodesy	Colonel A. R. Clarke, C.B., F.R.S., R.E.
Glossary of Navigation	Chaplain and Naval Instructor J. B. Harbord, M.A., R.N.
Hydrographical Surveying	Rear-Admiral Sir W. J. Wharton, K.C.B., R.N. Rear-Admiral Mostyn Field, F.R.S., R.N.
Lehrbuch der Navigation (Reichs-Marine-Amt.)	
Magnetism, General and Terrestrial.	Humphrey Lloyd, D.D., D.C.L.
Mathematical Instruments	J. F. Heather, M.A. A. T. Walmisley, M.I.C.E.
Maximum and Minimum Altitude and other Problems.	Staff Captain Charles Brent, R.N. Naval Instructor A. F. Walter, R.N. Naval Instructor George Williams, R.N.
Meteorology, Practical and Applied.	Sir John Moore, M.A., M.D., D.P.H., D.Sc., F.R.C.P.
Modern Navigation	Chaplain and Naval Instructor William Hall, B.A., R.N.
Navigation and Compass Deviations.	Commander W. C. P. Muir, U.S. Navy.
Navigation and Nautical Astronomy.	Staff Commander W. R. Martin, R.N.
Navigation and Nautical Astronomy.	Chaplain and Naval Instructor F. C. Stebbing, M.A., R.N.
Papers in the Philosophical Transactions of the Royal Society, 1860, 1861.	Archibald Smith, F.R.S. Captain F. J. Evans, F.R.S., R.N.
Popular Lectures and Addresses.	Sir William Thomson, LL.D., F.R.S., F.R.S.E.
Practical Manual of Tides and Waves.	W. H. Wheeler, M.I.C.E.
Practice of Navigation	Lieutenant Henry Raper, F.R.A.S., F.R.G.S., R.N.
Principal Winds and Currents of the Globe.	Captain R. Jackson, R.N.
Spherical and Practical Astronomy.	William Chauvenet.
Star Atlas	R. A. Proctor.
Tides and Kindred Phenomena.	Sir G. H. Darwin, K.C.B., F.R.S.
Watch Makers' Handbook	F. J. Britten.
Wrinkles in Practical Navigation.	Captain S. T. S. Lecky, F.R.A.S., F.R.G.S., R.N.R.

And numerous Government publications.

CONTENTS.

PART I.—NAVIGATION AND NAUTICAL ASTRONOMY.

CHAPTER I.

Positions on the earth's surface.

Article PAGE

1. Figure of the earth - - - - - - 1
2. Angular latitude and longitude - - - - 1
3. Circle of curvature of a meridian - - - - 2
4. The nautical mile - - - - - - 2
5. Length of a nautical mile - - - - - 3
6. The geographical mile - - - - - - 3
7. Length of the geographical mile - - - - 4
8. Linear latitude and longitude - - - - - 4
9. The knot - - - - - - - 5
10. The earth approximately a sphere - - - - 5
11. Difference of latitude and difference of longitude - - 6

CHAPTER II.

Direction on the earth's surface.

12. True bearing - - - - - - - 7
13. The magnetic compass - - - - - 7
14. Magnetic variation - - - - - - 8
15. Deviation of the compass - - - - - 9
16. Methods of applying deviation and variation - - - 10
17. The gyro-compass - - - - - - 12

CHAPTER III.

The course and distance by the Mercator's chart.

18. The rhumb line. Course and distance - - - 13
19. Relation between the arc of a parallel of latitude and the corresponding arc of the equator - - - - 14
20. The Mercator's chart - - - - - - 15
21. Construction of a Mercator's chart - - - 17
22 Plotting positions on a Mercator's chart - - - 20
23. To find the compass course from one position to another - 20
24. To find the distance from one position to another - - 22
25. To allow for a current when finding the course - - 23

CHAPTER IV.

THE COURSE AND DISTANCE BY CALCULATION.

Article PAGE
26. Fundamental formulæ for the rhumb line - - - 25
27. Formula for the departure - - - - - 26
28. Formulæ for course and distance - - - - 26
29. Approximate formula for the departure - - - 27
30. Approximate method of finding the course and distance by the traverse table - - - - - - 29

CHAPTER V.

THE GREAT CIRCLE TRACK.

31. The gnomonic chart - - - - - - 31
32. Special cases of the gnomonic chart - - - - 35
33. Construction of a gnomonic chart - - - - 35
34. To draw the great circle track on the Mercator's chart - 38
35. Great circle track by calculation - - - - 41
36. Great circle track by Towson's tables - - - - 43
37. The composite track - - - - - - 45

CHAPTER VI.

THE DEAD RECKONING AND ESTIMATED POSITIONS.

38. The dead reckoning position - - - - - 47
39. The estimated position - - - - - 47
40. Working the reckoning by chart - - - - 49
41. Working the reckoning by calculation - - - 51
42. Current by difference between dead reckoning and observed positions - - - - - - - 53
43. Keeping the reckoning in a tideway - - - - 53
44. Track of a ship while turning - - - - - 55
45. Keeping the reckoning during manœuvres - - - 56
46. Examples of keeping the reckoning during manœuvres - 63

CHAPTER VII.

POSITION LINE BY OBSERVATION OF TERRESTRIAL OBJECTS.

47. Unreliability of the estimated position. Position line - 67
48. Position line by compass bearing - - - - 68
49. Position line by horizontal sextant angle - - - 69
50. Position line by distance from an object - - - 69
51. Terrestrial refraction - - - - - - 70
52. Abnormal refraction - - - - - - 70
53. Altitude of a terrestrial object - - - - 71
54. Depression of a terrestrial object - - - - 71
55. The observer's sea and shore horizons - - - 71
56. Formula for the dip of the sea horizon - - - 72
57. Distance of the sea horizon - - - - - 73
58. Formula for the dip of the shore horizon - - - 74
59. Distance by vertical sextant angle - - - - 75
60. Lecky's Off-Shore Distance Tables - - - - 80

CHAPTER VIII.

POSITION BY OBSERVATION OF TERRESTRIAL OBJECTS.

Article PAGE
61. To fix the position of a ship - - - - - 81
62. Position by cross bearings - - - - - 81
63. Position by bearing and horizontal sextant angle - - 82
64. Position by bearing and distance - - - - 84
65. Position by horizontal sextant angles - - - - 84
66. Running fix - - - - - - - 88
67. Use of soundings in obtaining the position - - - 90

CHAPTER IX.

THE HEAVENLY BODIES AND THEIR TRUE PLACES.

68. Necessity for astronomical observations - - - 92
69. The stars - - - - - - - 92
70. The constellations - - - - - - 92
71. Designation of bright stars - - - - - 92
72. Magnitudes of stars - - - - - - 92
73. The solar system - - - - - - 93
74. The nebular theory - - - - - - 94
75. How to recognise the stars - - - - - 95
76. The movement of the earth - - - - - 97
77. The celestial concave. The ecliptic and celestial equator - 97
78. Positions of heavenly bodies - - - - - 99
79. Variation in right ascension and declination - - - 100

CHAPTER X.

THE GREENWICH DATE AND CORRECTION OF RIGHT ASCENSION AND DECLINATION.

80. The year and the month - - - - - 101
81. Celestial meridians of observer and heavenly body - - 101
82. The day - - - - - - - 102
83. The solar day - - - - - - - 102
84. The mean solar day and mean solar time - - - 102
85. Change of time for change of longitude - - - 103
86. The Greenwich date - - - - - - 104
87. Correction of right ascension and declination - - 105
  (*a*) The sun.
  (*b*) The moon.
  (*c*) The planets.
  (*d*) The stars.
88. Adjusting ship's clocks for change of longitude - - - 107
89. Standard times - - - - - - 108

CHAPTER XI.

THE ZENITH DISTANCE AND AZIMUTH AT THE ESTIMATED POSITION.

Article PAGE

90. Connection between a position on the earth and a heavenly body - - - - - - - 110
91. The azimuth - - - - - - - 110
92. The zenith distance - - - - - - 110
93. The astronomical triangle - - - - - 111
94. The hour angle - - - - - - 111
95. The equation of time - - - - - - 112
96. The right ascension of a meridian (or sidereal time) - - 112
97. Formula for the hour angle of a heavenly body - - 112
98. Correction of the equation of time - - - - 114
99. Change in the right ascension of the mean sun - - 115
100. Correction of the right ascension of the mean sun - - 115
101. Calculation of the zenith distance and azimuth at the estimated position - - - - - - 116
102. Azimuth tables and azimuth diagram - - - - 118

CHAPTER XII.

THE TRUE ZENITH DISTANCE AND ASTRONOMICAL POSITION LINE.

103. The true zenith distance - - - - - - 119
104. Formula for astronomical refraction - - - - 120
105. Semi-diameter - - - - - - - - 122
106. Parallax - - - - - - - - 123
107. Augmentation of the moon's semi-diameter - - - 124
108. Examples of the correction of altitudes - - - 125
109. The geographical position of a heavenly body - - 127
110. The true bearing of the geographical position - - 129
111. The circle of position - - - - - - 129
112. The astronomical position line - - - - 131
113. The most probable position from a single observation - 133
114. The value of a single position line - - - - 134

CHAPTER XIII.

POSITION BY ASTRONOMICAL POSITION LINES.

115. Position from two or more observations - - - 136
116. Examples of finding position by plotting and by calculation - 137
    Example (1).—Position from simultaneous observations by plotting (*a*) on chart, (*b*) on squared paper - - 137
    Example (2).—Position from simultaneous observations by calculation - - - - - - - 141
    Example (3).—Position from successive observations (*a*) by calculation, (*b*) by plotting on the chart - - 143
117. Error in a position due to error in the observed altitudes - 147

CHAPTER XIII.—*continued.*

Article PAGE

118. Error in a position due to uncertainty of the error of the deck watch - - - - - - - 149
119. Error in a position due to error in the observed altitudes and to uncertainty of the error of the deck watch - - 150
120. Error in a position due to error in the reckoning between the observations - - - - - - - 151
121. Error in a position due to error in the reckoning between the observations, and to the error in the observed altitudes 152
122. Error in a position due to error in the reckoning between the observations, to error in the observed altitudes, and to uncertainty of the error of the deck watch - - - 153
123. Particular case of very large altitudes - - - 153
124. Position by astronomical and terrestrial position lines - - 156

CHAPTER XIV.

OTHER METHODS OF DETERMINING AN ASTRONOMICAL POSITION LINE.

125. Meridian passages of heavenly bodies - - - - 157
  (*a*) The sun - - - - - - - 157
  (*b*) The stars - - - - - - 157
  (*c*) The moon - - - - - - 160
  (*d*) The planets - - - - - - 161
126. Position line by meridian altitude - - - - 161
127. Maximum and minimum altitudes - - - - 165
128. Position line by ex-meridian altitude - - - - 166
129. Position line by altitude of Polaris - - - - 170
130. Position line by "Longitude by chronometer" method - 173
131. Longitude by equal altitudes - - - - - 176
132. Notes on observations for determining position lines - - 182

CHAPTER XV.

RISING AND SETTING OF HEAVENLY BODIES, TWILIGHT, &c.

133. Hour angles of heavenly bodies when on the rational horizon - 185
134. S.M.T. of visible sun-rise and visible sun-set - - - 186
135. Twilight - - - - - - - 189
136. S.M.T. of visible moon-rise and visible moon-set - - 191
137. Identification of stars - - - - - - 192
138. Torrid, Frigid, and Temperate zones - - - - 194

CHAPTER XVI.

THE ERROR AND RATE OF THE CHRONOMETER.

Article PAGE

139. Meaning of the terms error, rate, and accumulated rate - 196
140. System of daily comparisons - - - - - 196
141. How to take time accurately with a deck watch - - 197
142. Error of the chronometer by time signal - - - 198
143. The mean comparison - - - - - - 199
144. Error of the chronometer by astronomical observation - 200
145. The artificial horizon - - - - - - 200
146. Observations in the artificial horizon - - - - 201
147. Error of the chronometer by absolute altitudes - - 204
148. Errors involved in absolute altitudes - - - - 208
149. Error of the chronometer by equal altitudes - - - 210
150. Formula for the equation of equal altitudes - - - 211
151. Errors involved in equal altitudes - - - - 212
152. Example of error of chronometer by equal altitudes - - 212
153. Summary of necessary comparisons - - - - 216
154. Notes on observations for error of chronometer - - 217
155. The rate of the chronometer - - - - - 220

PART II.—PILOTAGE.

CHAPTER XVII.

THE ADMIRALTY CHART AND ARTIFICIAL AIDS TO NAVIGATION.

156. Coasts - - - - - - - - - 222
157. Dangers - - - - - - - - 224
158. Depth of water - - - - - - - 225
159. Quality of the bottom - - - - - - 226
160. Tides and tidal streams. Currents - - - - 227
161. General abbreviations - - - - - - 227
162. System of buoyage in the United Kingdom - - - 229
163. System of lighting - - - - - - 232
164. Fog signals - - - - - - - 235
165. Reliability of fog signals - - - - - 236
166. Submarine bell - - - - - - - 237
167. Printing of the chart - - - - - - 238
168. Chart correction - - - - - - - 239
169. Reliability of charts - - - - - - 239
170. Sailing Directions - - - - - - 241

CHAPTER XVIII.

The track of the ship and the avoidance of danger in pilotage waters.

Article PAGE
171. The track - - - - - - - 242
172. Leading marks - - - - - - - 243
173. Lines of bearing - - - - - - 245
174. Turning on to a predetermined line - - - - 245
175. Clearing marks - - - - - - 250
176. Clearing bearings - - - - - - 250
177. The vertical danger angle - - - - - 250
178. The horizontal danger angle - - - - - 252
179. Avoidance of danger in thick weather - - - - 252
180. Preparing the chart - - - - - - 253
181. Selection of a position in which to anchor - - - 255
182. To anchor a ship in a selected position - - - 255
183. To moor a ship in a selected position - - - - 258
184. Example of the preparation of a chart with a view to anchoring 260
185. Conning the ship - - - - - - 262

PART III.—THE ATMOSPHERE AND OCEAN.

CHAPTER XIX.

The weather.

186. The atmosphere - - - - - - 264
187. The pressure of the atmosphere - - - - 264
188. Cause and direction of wind - - - - - 266
189. Permanent winds, Trades and Westerlies - - - 268
190. Periodic winds. Monsoons - - - - - 268
191. Land and sea breezes - - - - - - 269
192. Diurnal variation of the barometer - - - - 269
193. Local winds - - - - - - - 270
194. Causes of clouds, rain, etc. - - - - - 271
195. Causes of fog - - - - - - - 272
196. Atmospheric electricity - - - - - 272

CHAPTER XX.

Forecasting the weather.

197. The synoptic system of weather analysis - - - 274
198. The seven fundamental forms of isobars - - - 275
199. The cyclone - - - - - - - 276
200. The secondary cyclone - - - - - 277
201. The anti-cyclone - - - - - - 278
202. The wedge - - - - - - - 278
203. Straight isobars - - - - - - 279
204. The V depression - - - - - - 280
205. The col - - - - - - - 280
206. Revolving storms - - - - - - 280
207. The indications of the approach of a revolving storm - 283
208. Rules for determining the path of, and avoiding a revolving storm - - - - - - - - 284
209. Weather in the British Islands and North Sea - - 285
210. Storm signals - - - - - - - 287
211. Forecasting by a solitary observer - - - - 288

CHAPTER XXI.

OCEAN CURRENTS, WAVES, &C.

Article PAGE
212. Currents - - - - - - - 291
213. Atlantic Ocean stream currents - - - - 291
214. Pacific Ocean stream currents - - - - 293
215. Indian Ocean stream currents - - - - 294
216. Ocean waves - - - - - - - 294
217. To find the dimensions and period of a wave - - - 295
218. The specific gravity and colour of sea water - - - 296
219. Change of draught on passing from sea to river water - 297
220. Temperature of the sea - - - - - 297
221. Ice - - - - - - - - 298

CHAPTER XXII.

THEORETICAL TIDES.

222. The tide generating forces - - - - - 300
223. The horizontal tide generating force - - - - 303
224. The lunar and anti-lunar tides - - - - 303
225. The effect of the earth's rotation - - - - 304
226. The effect of declination - - - - - 305
227. The effect of parallax - - - - - - 306
228. The solar and anti-solar tides - - - - - 307
229. The composition of the lunar and solar tides - - - 307
230. Priming and lagging of the tide - - - - 309

CHAPTER XXIII.

OBSERVED TIDES AND USE OF TIDE TABLES.

TIDAL STREAMS.

231. Disagreement between theory and observation - - 311
232. Rise and range of a tide - - - - - 311
233. The primary and derived tide waves - - - - 313
234. The age of the tide - - - - - - 314
235. The amount of the priming and lagging - - - 315
236. The mean establishment of a port - - - - 315
237. To find the time of high water on any day from the mean establishment - - - - - - - 316
238. The vulgar establishment of a port, or the H.W.F. and C. - 317
239. To find the time of high water on any day from the H.W.F. and C. - - - - - - - - 317
240. Examples of finding the time of high water - - - 319
241. Diurnal inequality - - - - - - 320
242. Tide prediction. Standard ports - - - - 320
243. To find the height of the tide at any time, etc. - - 321
244. Examples of finding the height of the tide at any time - 322
245. Comparison between the tides at two places. Tidal constants 327
246. Effect of meteorological conditions - - - - 328
247. The cause of tidal streams - - - - - 329
248. Tidal streams in a channel - - - - - 329
249. Times of turning of tidal streams - - - - 330
250. The rates of tidal streams - - - - - 330
251. The tidal streams round the British Islands - - - 331

PART IV.—NAVIGATIONAL INSTRUMENTS.

CHAPTER XXIV.

THE MAGNETIC COMPASS.

THE MAGNETISM OF THE EARTH AND SHIP.

Article PAGE

252. Magnetism - - - - - - - 332
253. The effect of a magnet on an isolated pole - - - 334
254. The molecular theory of magnetism - - - - 336
255. Magnetic induction - - - - - - 336
256. Artificial magnets - - - - - - 338
257. Effects of temperature on magnets - - - - 340
258. Terrestrial magnetism - - - - - - 340
259. Changes in the variation - - - - - 341
260. Obtaining the variation by observation on shore - - 342
261. To find the true bearing of an object by observation - - 343
262. Example of finding variation on shore - - - 344
263. Local attraction - - - - - - 347
264. The compass - - - - - - - 347
265. To compare the earth's horizontal force at two places - 348
266. The permanent magnetism of a ship - - - - 348
267. The induced magnetism of a ship - - - - 349
268. The horizontal forces at the compass when the ship heels - 355
269. The sub-permanent magnetism of a ship - - - 357

CHAPTER XXV.

THE MAGNETIC COMPASS—(*continued*).

THE ANALYSIS AND CORRECTION OF THE DEVIATION.

270. The deviation of the compass - - - - - - 358
271. The principle of compass correction - - - - 360
272. The exact expression for the deviation of the compass - 360
273. The meaning of λ - - - - - - 362
274. The approximate expression for the deviation - - - 363
275. The component parts of the deviation - - - - 363
276. Relations between the exact and approximate coefficients - 365
277. To find the approximate coefficients from observation - 365
278. To find the exact coefficients - - - - - 367
279. The correction of coefficient B' - - - - 367
280. The correction of coefficient C' - - - - 369
281. The correction of coefficient D' - - - - 370
282. The correction of coefficient E' - - - - 372
283. The correction of the total quadrantal deviation - - 372
284. The induction in the soft iron correctors due to the compass needles - - - - - - - 375
285. The coefficient A' - - - - - - - 376
286. To obtain λ by observation - - - - - 376
287. The effect of spheres on λ and the formula for λ_2 - - 378
288. The effect of sub-permanent magnetism - - - 379
289. The effect of lightning - - - - - - 380
290. The expression for the deviation when the ship heels - - 380
291. The meaning of μ - - - - - - 382
292. The correction of the heeling coefficient J - - - 382
293. The heeling error instrument - - - - - 383
294. The correction of heeling error in harbour - - - 384
295. The correction of heeling error at sea - - - - 385
296. The change of the heeling error due to change of magnetic latitude - - - - - - - 386

CHAPTER XXVI.

THE MAGNETIC COMPASS—(*continued*).

THE DESCRIPTION AND PRACTICAL CORRECTION OF THE COMPASS.

Article		PAGE
297.	The bowl of the Chetwynd compass	388
298.	To remove a bubble from the compass	389
299.	The binnacle	390
300.	The Thomson compass	392
301.	The azimuth mirror	392
302.	How to take bearings	393
303.	The bearing plate or Pelorus	395
304.	The compass in a conning tower	396
305.	Precautions to be observed with regard to electrical instruments, &c.	397
306.	To obtain the deviation by observation	400
307.	To find the true bearing of an object by the Mercator's chart	403
308.	The adjustment of compasses	404
309.	To obtain the deviation of and to adjust a between-deck compass	406
310.	Swinging ship for deviation	406
311.	Necessity for frequent observations for deviation	409
312.	The criteria of a good deviation table	409
313.	Obtaining the variation by observation at sea	410

CHAPTER XXVII.

THE GYRO-COMPASS.

314.	Gyrostats and gyroscopes	411
315.	The effect of a couple on a gyrostat	411
316.	The effect of the earth's rotation on a gyroscope	412
317.	The effect of the earth's rotation on a gyroscope suspended from a point above its centre of gravity	413
318.	The damping of the oscillations of a gyroscope	415
319.	The effect on a gyroscope when carried on board ship	416
320.	The effects of the rolling and pitching of the ship on a gyroscope	417
321.	Description of the "Sperry" gyro-compass	418
322.	Damping of the oscillations of and the automatic correction of the "Sperry" gyro-compass	419
323.	The "Sperry" receivers	420
324.	Description of the "Anschütz" (three gyro) gyro-compass	421
325.	Damping of the oscillations of and applying the corrections to the "Anschütz" (three gyro) gyro-compass	423
326.	The "Anschütz" receivers	424

CHAPTER XXVIII.

THE SEXTANT.

327.	The principle of the sextant	426
328.	Description of the sextant	428
329.	The vernier	429
330.	The sextant telescopes	430
331.	The sextant parallax	430
332.	The errors of the sextant	431
333.	The error of perpendicularity	432
334.	Side error	432
335.	Collimation error	432
336.	Index error	433
337.	Centering error	434
338.	Care and use of the sextant	436

CHAPTER XXIX.

The chronometer.

Article PAGE
339. The principle and general description of the chronometer 438
340. The driving mechanism 439
341. The winding and maintaining mechanism 440
342. The train 441
343. The motion work 441
344. The escapement 441
345. The balance 443
346. Time of oscillation of the balance 443
347. The thermal compensation of the chronometer 444
348. Testing of chronometers at the Royal Observatory 447
349. The formula for the rate 447
350. Variation of the rate due to age 448
351. Abnormal variations in the daily rate 448
352. To wind and start a chronometer 450
353. The stowage and care of chronometers on board ship 452

CHAPTER XXX.

Various instruments.

354. The patent log 454
355. The speed by steaming over a measured distance 455
356. The error of a patent log 456
357. The speed by the revolutions of the engines 457
358. The sounding machine 457
359. The depth by chemical tube 459
360. Change of depth by the number of fathoms of wire run out 461
361. How to take soundings 462
362. The station pointer 464
363. The marine barometer 465
364. The aneroid barometer 468
365. The barograph 469
366. Thermometers 469
367. The maximum thermometer 470
368. The minimum thermometer 471

Appendix A.—Extracts from the Abridged Nautical Almanac, 1914 473
Appendix B.—Daily weather report of the Meteorological Office. Change of units of measurement 489
Appendix C.—Hydrographical Surveying 449

INDEX.

PART I.—NAVIGATION AND NAUTICAL ASTRONOMY.

CHAPTER I.

POSITIONS ON THE EARTH'S SURFACE.

1. Figure of the earth.—As navigation is concerned with the successive positions of a ship as she passes from one place on the earth's surface to another, it necessarily involves a knowledge of that surface and a method of expressing positions on it.

The earth is an oblate spheroid, whose greatest and least diameters are approximately 3,963 and 3,950 statute miles respectively. The earth turns about its shortest diameter which is called its axis, the extremities of the axis being called the poles of the earth.

An oblate spheroid is a figure traced out by the revolution of a semi-ellipse, such as PQP' in Fig. 1, about its minor axis PP'. The successive positions of PQP' are called meridians. That meridian which passes through the transit instrument at the Royal Observatory at Greenwich is called the prime meridian.

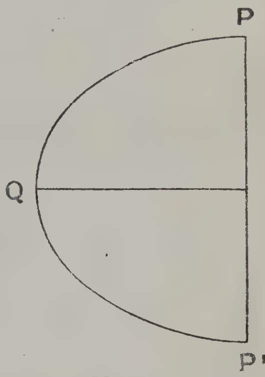


FIG. 1.

The circle traced out by the point Q, which is the extremity of the semi-major axis of the ellipse, is called the equator.

The earth revolves about its axis PP' in the direction shown by the arrows in Fig. 2. The direction of revolution is called East, and the opposite direction is called West. If we look East, the direction perpendicular to East on our left hand is called North, and that on our right hand is called South. That pole of the earth which is situated on our left hand, P in Fig. 2, is called the North pole, and that situated on our right hand, P', is called the South pole.

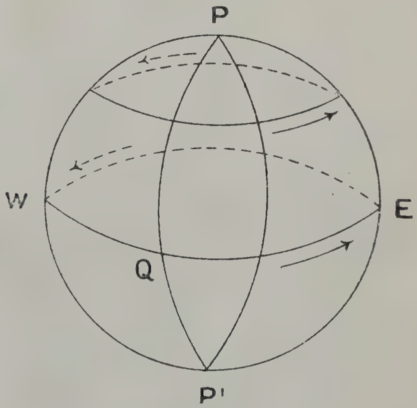


FIG. 2.

2. Angular latitude and longitude.—A position on the surface of the earth is expressed by reference to the plane of the equator, and the plane of the prime meridian.

The angular latitude (also called the geodetic, geographical or true latitude) of a place is the angle which the perpendicular to the earth's surface at the place makes with the plane of the equator; it is measured from 0° to 90°, and is named North or South according as the place is North or South of the equator; thus, the angular latitude of *O*, in Fig. 3, is the angle *OXE*.

The co-latitude of a place is the complement of the latitude, that is, 90° − latitude of the place.

Small circles of the earth, whose planes are parallel to the plane of the equator, are called parallels of latitude.

The angular longitude of a place is the angle between the planes of the prime meridian and the meridian of the place. It is measured from 0° to 180°, and is named East or West according as the place is East or West of the prime meridian.

3. Circle of curvature of a meridian.—In Fig. 3, let *O* be any point on the meridian, then an infinite number of circles may be drawn in the plane of the meridian to touch the meridian at this point, and there is one particular circle which most nearly coincides with the meridian in the neighbourhood of *O*; this circle is called the circle of curvature at *O*, its radius *OK* is called the radius of curvature and its centre *K* is called the centre of curvature.

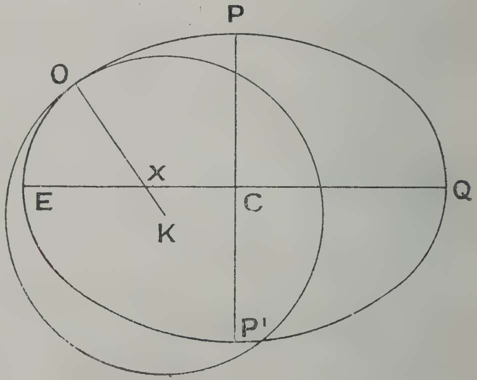


Fig. 3.

It will be seen from the figure that the radius of curvature increases as *O* moves from the equator to either pole.

4. The nautical mile.—The sea or nautical mile at any place is the length of an arc of the meridian, in the vicinity of that place, which subtends an angle of one minute at the centre of curvature.

In Fig. 4 let *O* be a place on the earth's surface, and *K* the centre of curvature at *O*. Then, if *AB* is an arc of the meridian which contains *O* and subtends an angle of 1′ at *K*, the length of *AB* is the length of the sea or nautical mile at *O*.

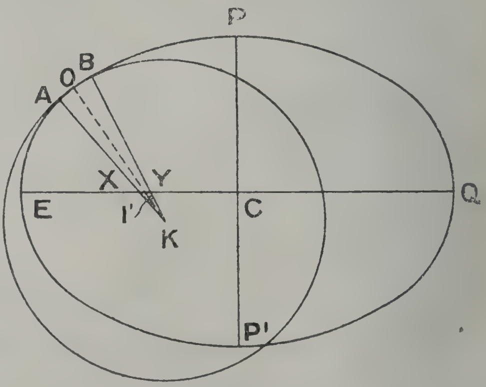


Fig. 4.

Since KA and KB are perpendicular to the circle of curvature at A and B, and since the circle of curvature coincides with the meridian along the small arc AB, it follows that KA and KB are perpendicular to the meridian. Therefore, if ECQ is the line where the plane of the meridian is cut by the plane of the equator, AXE and BYE are the angular latitudes of A and B respectively.

$$\text{Now } BYX - AXE = BKX = 1'.$$

Therefore the latitude of B − the latitude of $A = 1'$, and we see that the nautical mile may be regarded as the length of an arc of the meridian, in the vicinity of the place, intercepted between two points whose angular latitudes differ by $1'$.

5. Length of a nautical mile.—It may be shown that if r is the radius of curvature of a meridian at a place whose latitude is L,

$$r = \frac{a+b}{2} - 3\frac{a-b}{2}\cos 2L, \text{ nearly,}$$

where a and b are the greatest and least radii of the earth respectively.

In Fig. 4 the arc $AB = AK \times$ c.m. of AKB.

$$= AK \times \text{c.m. of } 1'$$
$$= AK \sin 1'.$$

Therefore, denoting the arc AB, which is the length of a sea or nautical mile at O, by n; and denoting AK, which is the length of the radius of curvature at O, by r; we have

$$n = r \sin 1'$$

Therefore, from above

$$n = \left[\frac{a+b}{2} - 3\,\frac{a-b}{2}\cos 2L\right]\sin 1'$$

Now $a = 2{\cdot}09262 \times 10^7$ feet

and $b = 2{\cdot}08549 \times 10^7$ feet

and substituting these values, we find that the length of the sea or nautical mile in latitude L is given by

$$n = [6076{\cdot}8 - 31{\cdot}1 \cos 2L] \text{ feet.}$$

It will be seen from this equation that the sea or nautical mile varies with the latitude, being shortest at the equator where its length is 6045·7 feet and longest at the poles where its length is 6107·9 feet. The lengths of the nautical mile, in various latitudes, are given in Inman's Tables.

For convenience, when discussing small distances, the tenth part of a nautical mile is called a cable.

6. The geographical mile.—The geographical mile is the length of an arc of the equator which subtends an angle of $1'$ at the centre of the earth. The equator being a circle, the length of the geographical mile is the same at all parts of the equator.

7. Length of the geographical mile.—In Fig. 5 let ED be an arc of the equator which subtends an angle of $1'$ at its centre C, then the length of ED is the length of the geographical mile.

Now $ED = CE \times$ c.m. of $ECD = EC \times$ c.m. of $1' = EC \sin 1' = a \sin 1'$. The length of the geographical mile is 6087·1 feet.

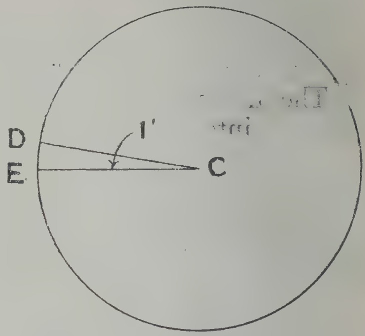


FIG. 5.

8. Linear latitude and longitude.—The position of a place on the earth's surface may be expressed by reference to the equator and prime meridian.

The linear latitude of a place is the length of the arc of the meridian of the place intercepted between the equator and the place. It is measured in nautical miles, and is named North or South according as the place is North or South of the equator.

In Fig. 6 let the meridian EP be divided into sea or nautical miles at the points G, H, &c.; then, since EG is a nautical mile, and since a nautical mile is an arc of a meridian between two places whose latitudes differ by $1'$, the angular latitude of G must be $0° 1'$ N. Similarly, since GH is a nautical mile, the angular latitude of H must differ from that of G by $1'$, and must therefore be $0° 2'$ N., and so on. If the length of EB is 40×60 or 2,400 sea or nautical miles, the angular latitude of B must be 40° N.

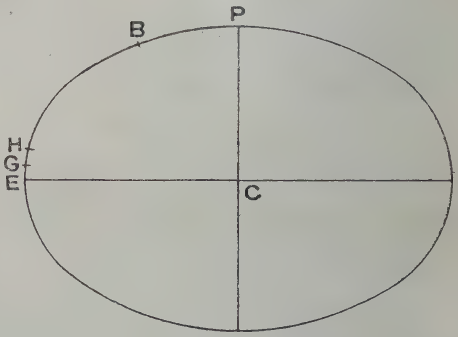


FIG. 6.

We may, therefore, say that, if a place is in latitude 10° N., the length of the arc of the meridian, intercepted between the equator and the place, is 600 nautical miles.

Conversely, if a place is situated 300 nautical miles North of the equator, its angular latitude is $\frac{300}{60}$ or 5° N.

It is customary to write 1 nautical mile as $1'$ and 60 nautical miles as $1°$, because if a place is situated a particular number of nautical miles North or South of the equator, the angular latitude of the place contains the same number of minutes of arc.

It should be remembered that linear latitude is a measurement of length and not angle, and if we refer to a linear latitude 10° N., we refer to a length along the meridian of 600 nautical miles measured in a Northerly direction from the equator.

Linear longitude of a place is the smaller arc of the equator intercepted between the prime meridian and the meridian of the place; it is expressed in geographical miles and is named East or West according as the place is East or West of the prime meridian.

Let us suppose that the equator is divided into geographical miles, then, since the geographical mile is the length of an arc which subtends $1'$ at the centre, two geographical miles subtend $2'$ at the centre, three geographical miles subtend $3'$ and so on. For this reason, it is usual to write a geographical mile as $1'$, and to write 60 geographical miles as $1°$; but it should be remembered that linear longitude is a measurement of length and not angle, and if we refer to a linear longitude 10° E., we refer to a length along the equator of 600 geographical miles measured in an Easterly direction from the prime meridian.

9. The knot.—In navigation the unit of speed is the speed of one nautical mile per hour, and this unit is called the knot. A ship, steaming 10 nautical miles per hour, is said to be steaming 10 knots, and this should never be expressed as "10 knots per hour."

As it is impracticable to construct speed recording instruments, such as patent logs, to register the length of a nautical mile as it varies in different latitudes, it becomes necessary to decide upon some suitable length for the nautical mile which these instruments may be constructed to indicate. The length decided on is 6,080 feet, and the British Admiralty knot is therefore a speed of 6,080 feet per hour. The reason for the adoption of this length is uncertain, but it is supposed to have been taken because it is the nearest round number to 6082·2 which is the length in feet of the nautical mile in the English Channel.

10. The earth approximately a sphere.—Although the earth is an oblate spheroid, for nearly all purposes of navigation it is sufficiently accurate to assume it to be a sphere whose radius is the mean of the earth's greatest and least radii, that is, $2{\cdot}089055 \times 10^7$ feet. The errors involved in this assumption are very small and entirely lost in practice amongst the many other errors incidental to navigation.

On the assumption that the earth is a sphere, the length of an arc of a meridian subtending an angle of $1'$ at the centre is 6,077 feet, and this length is the same as the mean length of a sea or nautical mile between the equator and the poles; therefore, this length to the nearest round number, that is 6,080 feet, has been taken as the length of the mean nautical mile which is the same as the length on which the Admiralty knot is based. This value of the mean nautical mile gives a mean value for the cable of 202·7 yards. It is customary to regard a cable as 200 yards, which is the same as the length of eight shackles of chain cable, called a "cable's length," a shackle being $12\frac{1}{2}$ fathoms or 25 yards long.

Another reason for regarding the earth as a sphere is that the linear latitude and linear longitude are then measured in the same units, namely, the length of a mean nautical mile, and there is no further need to consider the geographical mile, or to draw a distinction between angular latitude and longitude and linear latitude and longitude in numerical calculations. Under the worst conditions arising from this assumption, the error in the linear latitude cannot exceed ·31 per cent., while that in the linear longitude cannot exceed half this value.

It should be noticed that when we regard the earth as a sphere, the meridians become semi-great circles, and the angular latitude of a place is the angle at the centre between the plane of the equator and the radius of the earth which passes through the place.

11. Difference of latitude and difference of longitude.—One position on the earth's surface is related to another by the difference of latitude and difference of longitude.

The difference of latitude between two places, usually written *d* Lat., is the length of the arc of a meridian intercepted between the parallels of latitude through the two places. If a ship is proceeding from one place to another, the difference of latitude is named North or South according as the parallel of the destination is North or South of the parallel of the place of departure.

The difference of longitude between two places, usually written *d* Long., is the length of the smaller arc of the equator intercepted between their meridians. The difference of longitude is named East or West according as the meridian of the destination is East or West of the meridian of the place of departure.

Let F be the place from which the ship starts and T the place to which she is bound.

Suppose that F is in Lat. 15° 30′ N. and Long. 40° 20′ W.
and T is in Lat. 60° 27′ N. and Long. 15° 30′ E.
then the *d* Lat. is 44° 57′ N. and the *d* Long. 55° 50′ E.

It should be noted that these two measurements are both linear and are both in nautical miles, so that the *d* Lat. may be more correctly expressed as 2,697′ N. and the *d* Long. as 3,350′ E.

CHAPTER II.

DIRECTION ON THE EARTH'S SURFACE.

12. True bearing.—We have shown how a position on the earth's surface is determined by latitude and longitude ; it is now necessary to consider how to determine the direction of one position from another.

The direction of any point on the surface of the earth from an observer is known, if we know the angle at the observer between his meridian and the great circle passing through the observer and the point. This angle is called the true bearing or azimuth of the point, and is measured from North or South towards East or West from 0° to 90°, or it may be measured from North, clockwise from 0° to 360°. In Fig. 7 the true bearing of the point *S* from the observer *O* may be called S. 40° W. or 220°.

The direction of the ship's head at any moment is the angle between the fore-and-aft line and the meridian, or, in other words, is the true bearing of the ship's stem from an observer on the fore-and-aft-line of the ship.

Since the meridians are imaginary semicircles, the angle between any meridian and a particular great circle cannot be directly measured, but by the aid of an instrument, called a compass, the direction of the meridian, and so the direction of any point, can be determined.

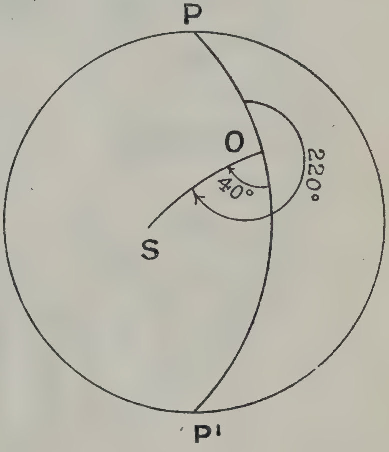


Fig. 7.

A compass is constructed to indicate direction under the influence of the earth's magnetism or of the earth's rotation ; in the former case it is called a magnetic compass, and in the latter a gyro-compass.

13. The magnetic compass.—The magnetic compass consists of a bowl, in the centre of which is pivoted a magnetic needle or system of needles, to which is attached a circular card, so suspended that it is free to revolve about its centre and to take up a definite position under the action of the earth's magnetism. The bowl is suspended from gimbals in order that the pivot may be always vertical, and the gimbals are supported by a pedestal called the binnacle. The position taken up by the needle at any place, when unaffected by local attraction, is such that the needle points in a known direction which is called magnetic North at that place, and the great circle of the earth in which the compass needle lies is called the magnetic meridian of that place.

In Fig. 8 a compass card is shown graduated in 32 divisions of 11° 15′ each, called points. Each quadrant is divided into 90 degrees, starting from North and South. The card is so attached to the compass needle or needles that the line joining the North and South points of the card is parallel to the needle or needles.

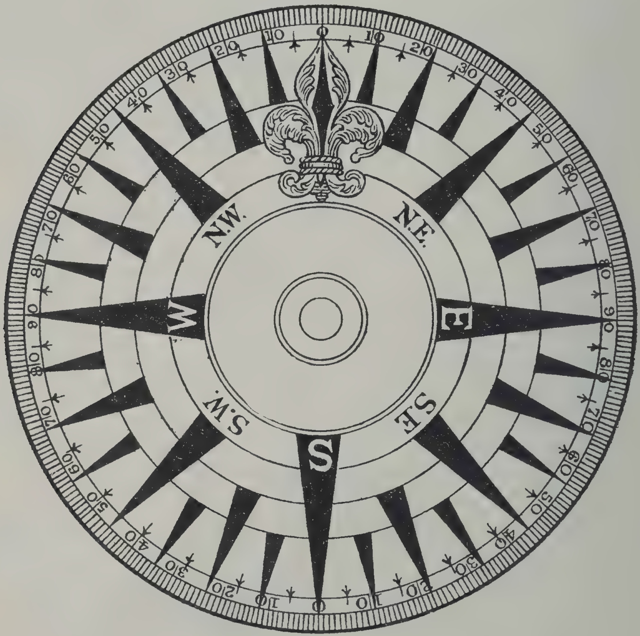


Fig. 8.

As regards the division into points, N., S., E. and W. are called the cardinal points; the points situated midway between the cardinal points are called the quadrantal points; the arcs between the cardinal and quadrantal points are further divided as shown in Inman's Tables, page 1, which should be studied in connection with Fig. 8.

14. Magnetic variation.—The direction of the magnetic meridian at any place differs from that of the true meridian by an angle which is called the variation. Variation is named East or West according as the magnetic North lies East or West of the meridian of the place.

The variation is different at different places and its ascertained values are shown diagramatically on a chart, called the variation chart, by the curves of equal variation.

The variation changes slightly from year to year, and care should therefore be taken that the correct variation is used; the annual change in variation for all places is given on the variation chart.

It will thus be seen that, if we know the variation and the direction of magnetic North, we know the direction of the true meridian; therefore, at sea, by aid of the magnetic compass and the variation chart, we know the directions of two meridians which intersect at the observer, namely, the magnetic and true meridians; consequently, the direction of any point may be referred to either one of these meridians. The bearing of a point, when measured from the true meridian, is called the true bearing, and, when measured from the magnetic meridian, it is called the magnetic bearing.

For example, suppose that an observer *O* is at a place where the variation is 20° W., and that the compass needle lies along the line *OM* (Fig. 9), which is the magnetic meridian. The line *OT* which is drawn so that the angle *TOM* is 20°, and *M* is to the West of *T*, is the true meridian. It will be seen that the direction of North (true) is N. 20° E. (Mag.).

Again, if *OX* is the great circle which passes through the observer *O* and a point *X*, and if the angle *MOX* is 60°, the magnetic bearing of *X* is N. 60° W. The angle *TOX* being 80°, the true bearing of *X*, is N. 80° W. (280°).

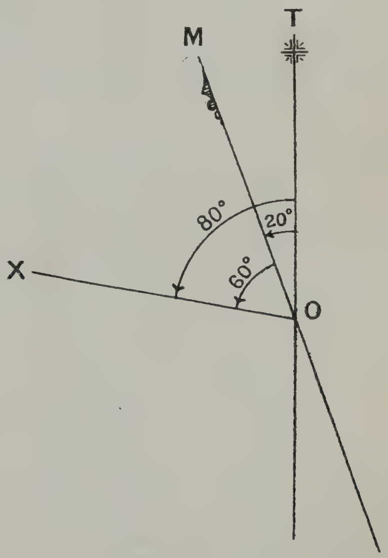


Fig. 9.

15. Deviation of the Compass.

—On account of the magnetism in the iron and steel of which the ship is constructed, the compass needle may not lie exactly in the magnetic meridian but to one or other side of it. The angle between the compass needle and the magnetic meridian is called the deviation, and is named East or West according as the North seeking end of the needle lies to the East or West of the magnetic meridian.

In a ship there are generally several compasses, one of which is in a very carefully selected position in order that it may be affected as little as possible by the magnetism of the ship ; this compass is called the standard compass. The other compasses are situated at the various steering positions, and observations taken with them must always be checked by comparison with the standard compass.

Each compass is provided with a mark or pointer called the lubber's point, situated inside the bowl and close to the edge of the compass card, and in such a position that the line joining it to the centre of the compass card is parallel to the fore-and-aft line of the ship ; therefore the graduation of the compass card which is opposite to the lubber's point gives the direction of the ship's head as indicated by that particular compass card.

As the compasses are differently situated with regard to the iron and steel of the ship, they are differently affected by the ship's magnetism, and consequently two compasses, similar in every respect but situated in different parts of the ship, generally have entirely different deviations.

In general the deviation of a compass is different for different directions of the ship's head, and is obtained for various directions of the ship's head by observation.

A specimen deviation table, such as is made out and hung up in the vicinity of the compass to which it applies, is shown below :—

Ship's Head.	Deviation.			Ship's Head.	Deviation.		
	°	′			°	′	
N.	2	00	E.	S.	2	00	W.
N. by E.	2	25	E.	S. by W.	0	45	W.
N.N.E.	2	45	E.	S.S.W.	0	40	E.
N.E. by N.	3	00	E.	S.W. by S.	1	55	E.
N.E.	3	00	E.	S.W.	3	00	E.
N.E. by E.	2	40	E.	S.W. by W.	3	45	E.
E.N.E.	2	00	E.	W.S.W.	4	10	E.
E. by N.	1	10	E.	W. by S.	4	15	E.
E.	0	00		W.	4	00	E.
E. by S.	1	10	W.	W. by N.	3	30	E.
E.S.E.	1	20	W.	W.N.W.	2	55	E.
S.E. by E.	3	15	W.	N.W. by W.	2	20	E.
S.E.	3	50	W.	N.W.	1	50	E.
S.E. by S.	4	00	W.	N.W. by N.	1	30	E.
S.S.E.	3	45	W.	N.N.W.	1	30	E.
S. by E.	3	00	W.	N. by W.	1	40	E.

This table will be referred to in working examples throughout the book.

16. Methods of applying deviation and variation.—We have now to find the direction of the ship's head (magnetic) and ship's head (true), when the direction of the ship's head by compass is known ; for example, suppose that the ship's head by the compass, the deviation table for which is given above, is N. 50° W., and that it is required to find the direction of the ship's head (magnetic). On reference to the table, we see that the deviations are given for every point (11° 15′), and as N. 50° W. lies between N.W. and N.W. by W., we take the deviation as 2° 00′ E.

In Fig. 10 let *OM* represent the magnetic meridian, and *OC* the direction of the North point of the compass needle, so that the angle *MOC* is 2°, and *C* lies to the East of *M*. Let the line *OH* represent the direction of the ship's head or lubber's point, the angle *COH* being 50°. Then it will be seen that the angle *MOH* is 48°, so that the direction of the ship's head is N. 48° W. (Mag.). If the variation at the ship, from the variation chart, is found to be 20° W., let the line *OT* represent the true meridian, so that the angle *TOM* is 20° and *M* lies to the West of *T*; then it will be seen that the angle *TOH* is 68°, so that the direction of the ship's head is N. 68° W. (true) (292°).

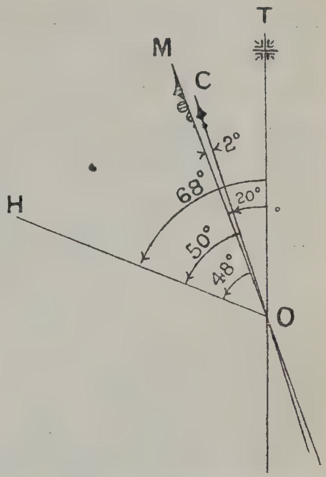


Fig. 10.

In order to avoid mistakes, the student is recommended to draw figures when applying variation and deviation, but circumstances may arise when this is impracticable, and so we must have some rules by which the operation can be carried out mentally; these rules are as follows:—

(*a*) Given the compass direction to find the magnetic (or given the magnetic to find the true):—

> Imagine yourself to be standing at the centre of the compass card and looking in the given direction; apply Easterly deviation (or variation) to the right, and apply Westerly deviation (or variation) to the left.

(*b*) Given the true direction to find the magnetic (or given the magnetic to find the compass):—

> Reverse the rule above, that is, apply Easterly variation (or deviation) to the left, and apply Westerly variation (or deviation) to the right.

As some compass cards are now graduated from 0° to 360° (from North through East), it is convenient when using them to name Easterly deviations and variations +, and Westerly deviations and variations −.

(*a*) and (*b*) now become:—

(*a*) Apply deviation and variation *according to* their algebraical signs.

(*b*) Apply deviation and variation *contrary to* their algebraical signs.

The following examples illustrate the application of these rules :—

(*a*)

Ship's head (compass)	S. 50° 00′ E.	or 130° 00′
Deviation from table	3 30 W.	— 3 30
Ship's head (Mag.)	S. 53° 30′ E.	or 126° 30′
Variation from chart	20 00 W.	— 20 00
Ship's head (true)	S. 73° 30′ E.	or 106° 30′

(*b*)

Ship's head (true)	N. 40° 00′ W.	or 320° 00′
Variation from chart	20 00 W.	— 20 00
Ship's head (Mag.)	N. 20° 00′ W.	or 340° 00′
Deviation from table (for N. 20° W.)	1 30 E.	+ 1 30
Ship's head (compass)	N. 21° 30′ W.	or 338° 30′

17. The gyro-compass.—The gyro-compass is an instrument surmounted by a card which is graduated in a similar manner to that of the magnetic compass, Fig. 8, except that the degrees are marked from 0° to 359° from North through East, and indicates true directions in obedience to the mechanical laws on which it is based. There is a slight correction, due to the course and speed of the ship, which has to be applied to the bearings indicated by it ; this correction is explained in Part IV.

The movements of the gyro-compass are communicated electrically to receivers which are placed as convenient in different parts of the ship.

CHAPTER III.

THE COURSE AND DISTANCE BY THE MERCATOR'S CHART.

18. The rhumb Line. Course and distance.—We are now led to the consideration of the problem of how to pass from one position on the earth's surface to another.

As when about to set out for a place by land, so in setting out for a place by sea, the first question that arises, is, Which is the way? Neglecting other considerations, it will obviously be of great advantage if the direction of the ship's head is the same at all points of the track, that is if the track cuts all the meridians at the same angle. Now a line on the earth's surface which cuts all the meridians at the same angle is called a rhumb line. If, therefore, two places on the earth's surface are joined by a rhumb line and the ship steered along this line the direction of the ship's head will remain the same; this direction is called the course. The course is measured from North or South, according as the *d* Lat. is N. or S., from 0° to 90° towards East or West, according as the *d* Long. is E. or W. (§ 11).

The equator, parallels of latitude and the meridians are all rhumb lines.

In Fig. 11 *F* is the place "From" which the ship starts, *T* is the place "To" which she is bound.

The curved line, *FABCT*, is the rhumb line joining the two places, and the angles *PFA*, *PAB*, *PBC*, *PCT*, &c., all being equal, any one of them may be regarded as the course.

The length of the rhumb line between *F* and *T*, expressed in nautical miles, is called the distance between *F* and *T*.

Now the shortest distance between two places is the arc of the great circle which joins them. A great circle, however, cuts the meridians at different angles, so that to steam along a great circle would necessitate constant alterations in the direction of the ship's head. We have therefore to choose between the rhumb line at every point of which the direction is the same, but which is

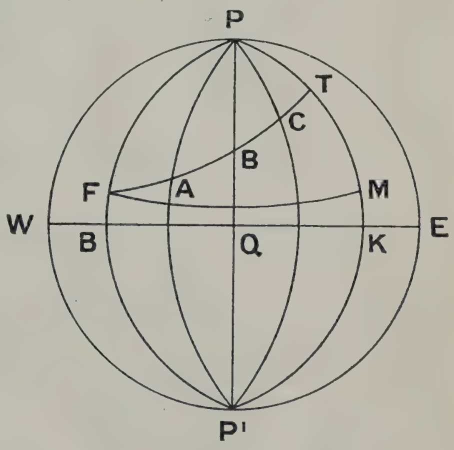


FIG. 11.

longer than the arc of the great circle, and the arc of the great circle at every point of which the direction is different but which is shorter than the rhumb line. The great convenience of keeping the ship's head in a constant direction, as well as the simplicity of the calculations involved in finding this direction, gives a preference to the rhumb line except over very long distances.

The irregular distribution of land and water, as well as the presence of rocks, shoals, &c. in the latter, frequently prevent a ship steaming along the rhumb line which joins the two places; therefore, before determining the course, it is necessary to discover if the rhumb line to her destination is interrupted by land or other obstacles, and if so, to determine one or more intermediate destinations, the rhumb lines between which are uninterrupted. For this purpose charts are constructed upon which the coast line, rocks, shoals, &c. are accurately depicted, and of such a nature that the rhumb line joining any two places is represented as simply as possible, that is, by a straight line.

The chart which serves these purposes is called a Mercator's chart, and we have now to explain its construction, but before doing so we shall give the proof of an important relation which is frequently required in navigation.

19. Relation between the arc of a parallel of latitude and the corresponding arc of the equator.— In Fig. 12, let eq be an arc of a parallel in latitude L, and let the meridians of e and q intersect the equator in E and Q respectively.

Let C and c be the centres of the arcs EQ and eq respectively.

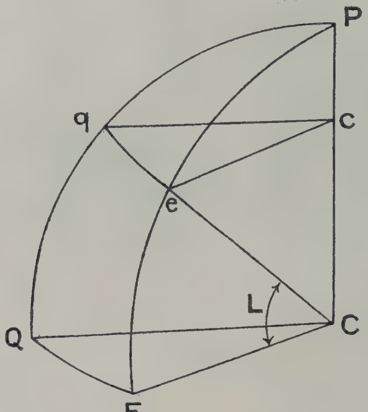


FIG. 12.

$$\begin{aligned} \text{Then arc } eq &= ec \times \text{c.m. of } ecq \\ &= ec \times \text{c.m. of } ECQ \\ &= ec \times \frac{EQ}{EC} = \frac{ec}{EC} \times EQ. \end{aligned}$$

Now

$$\frac{ec}{EC} = \frac{ec}{eC} = \sin cCe = \cos ECe = \cos L.$$

Therefore

$$eq = EQ \cos L$$
$$\text{or } EQ = eq \sec L.$$

20. The Mercator's chart.—The Mercator's chart is constructed on the following principles:—

(1) Rhumb lines on the earth's surface are represented by straight lines on the chart.

(2) Angles on the earth's surface are equal to the corresponding angles on the chart.

The equator is a rhumb line, and is therefore represented by a straight line on the chart. For simplicity, let us suppose that the chart is full sized; that is, let us suppose that the length of the line eq which represents the equator on the chart, Fig. 13, is equal to the length of the earth's equator. The distance between any two meridians at the earth's equator is consequently equal to the corresponding distance on the line eq.

The meridians are rhumb lines, and they cut the equator at right angles; therefore, from (1) and (2), the meridians are represented on the chart by a system of parallel straight lines at right angles to the line eq, and their distances apart on the chart are equal to their distances apart at the equator on the earth's surface.

The parallels of latitude are rhumb lines, and they cut the meridians at right angles; therefore, from (1) and (2) the parallels of latitude are represented on the chart by a system of parallel straight lines at right angles to the meridians.

We have now to find at what distance from eq, the various lines should be drawn which represent the parallels of latitude.

To do this, let us consider a rhumb line which does not run either North or South, as a meridian, or East or West, as a parallel of latitude.

Let FT be a rhumb line on the earth's surface, joining the point F on the equator to a point T, then FT by (1) is represented on the chart by a straight line ft.

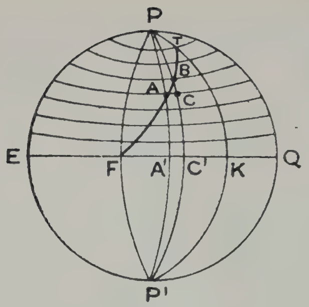
Let a large number of equidistant parallels of latitude be drawn between F and T, and let the length of a meridian intercepted between any consecutive two be dl.

Let the rhumb line FT intersect any two consecutive parallels in A and B.

Let the meridians of A and B intersect the equator in A' and C' respectively, and let the parallel of latitude through A intersect the meridian of B in C.

Let the corresponding points on the chart be denoted by small letters.

If CB, that is dl, is so small that the triangle CBA may be considered a plane triangle right-angled at C, then, since by



Earth.

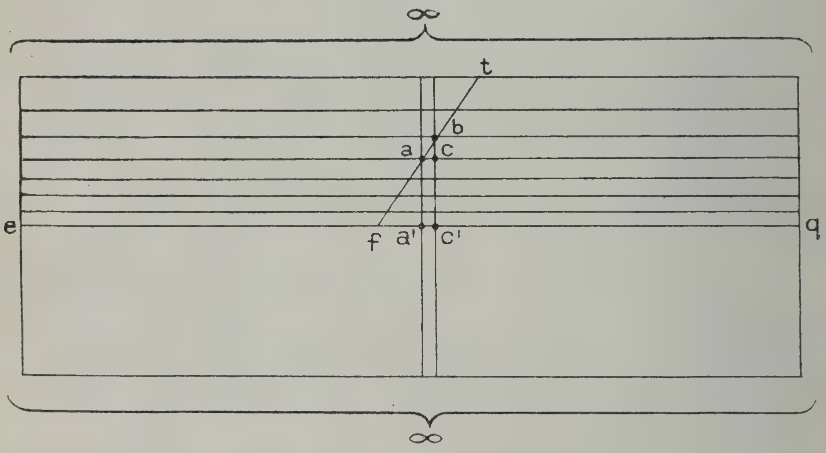


Chart.

FIG. 13.

(2) angles on the earth's surface are equal to the corresponding angles on the chart, the two triangles ABC, abc, are similar, and therefore

$$\frac{cb}{CB} = \frac{ca}{CA} = \frac{ca}{C'A' \text{ Cos } L} = \frac{1}{\text{Cos } L}$$

where L is the angular latitude of A, and the spheroidal form of the earth is neglected.

Therefore

$$cb = \frac{CB}{\text{Cos } L}$$

or

$$cb = dl \sec L$$

Therefore, if two near parallels of latitude intercept a length dl of a meridian, the corresponding length on the chart is $dl \sec L$, where L is the angular latitude of the lower parallel.

Let the angular latitude of B be $L + dL$, so that CB, that is dl, subtends an angle dL at the centre of the earth.

Then if B is on the n^{th} parallel, $L = (n - 1)\ dL$, and $cb = dl \sec (n - 1)\ dL$.

Therefore the length of $a'a$ on the chart is
$dl \sec 0 + dl \sec dL + dl \sec 2dL + \ .\ .\ + dl \sec (n-1)\, dL.$
Now $dl = R \times dL$, where R is the earth's radius.
Therefore

$$a'a = R \times dL\, [\sec 0 + \sec dL + \sec 2dL + \ .\ .\ .\ + \sec (n-1)\, dL.]$$

The value of this series, when n is infinite, is

$$R \log_e \tan \frac{90° + L}{2}$$

or, reduced to ordinary logarithms,

$$R \times 2\cdot302585 \times \log \tan \frac{90° + L}{2}$$

When R is expressed in nautical miles, the value of this expression is called the meridional parts (m.p.) for latitude L and is tabulated in Inman's Tables for every minute of arc from 0° to 90°. Therefore the distance on the full sized chart, between the line which represents the parallel of latitude L and the line which represents the equator, is the meridional parts for latitude L.

It follows that the length on the chart, between the lines which represent the parallels of latitude L and L', is the difference between the meridional parts for latitude L and the meridional parts for latitude L', and this difference is generally written d.m.p.

When $L = 90°$, the meridional parts become infinite and therefore the chart of the earth's surface extends to infinity in either direction perpendicular to the equator.

It will be seen that on the full sized Mercator's chart small lengths are $\sec L$ times their length on the earth's surface, and that small areas are $\sec^2 L$ times their areas on the earth's surface.

It should be noticed that

$$\frac{ft.}{\text{m.p}} = \frac{ab}{bc} = \frac{AB}{BC} = \frac{n.AB}{n.BC} = \frac{FT}{d.\text{Lat.}}$$

which is the relation between the distance *ft.* on the full-sized Mercator's chart and the actual distance *FT*.

21. Construction of a Mercator's chart.—To construct a chart of convenient size we should mentally construct a full sized chart, which we have just considered, and then reduce this according to some particular scale. Let us construct a chart of the earth's surface on a scale of 10° of longitude to the inch, the meridians and parallels to be drawn at every 20°.

The length of the equator is 360° or 360 × 60 nautical miles; therefore, since the chart is to be drawn on a scale of 10° or 600 nautical miles to the inch, the line representing the equator is 36 inches long. Draw a line of this length to represent the equator in the middle of the sheet.

Since the meridians are to be drawn at every 20°, and the scale is 10° of longitude to the inch, divide this line into 18 equal parts, each 2 inches long. Mark the left hand extremity of the line 180° W., and then, towards the right, mark the intermediate points of division 160° W., 140° W., &c. down to 0°, then 20° E. 40° E., &c., as far as the right hand extremity which mark 180° E. Through these points erect perpendiculars to represent the meridians.

We have now to draw the parallels of latitude at every 20°. On the full sized chart the distance of the parallel of latitude of 20° from the equator is the meridional parts for 20°. Now the meridional parts for 20° is 1225·14 nautical miles, and on a scale of 10° of longitude to the inch, which is the same as 600 nautical miles to the inch, this is represented by 2·04 inches. Draw two lines parallel to the equator on the chart at a distance of 2·04 inches from it; mark the extremities of the upper line 20° N. and the extremities of the lower line 20° S. These lines represent the parallels of 20° North latitude and 20° South latitude respectively. In the same way all the other parallels may be drawn.

The configuration of the land, the positions of rocks, shoals, &c. may now be placed on the chart by means of their respective latitudes and longitudes.

In order that charts may be on a large scale, it is necessary to construct them for portions of the earth's surface only. In such charts the equator may not be included, and the differences between successive parallels of latitude on the chart are found by reducing to inches, according to scale, the differences between the corresponding meridional parts.

As an example, let us construct a chart from 142° E. to 146° E., and from 54° N. to 58° N., the scale of the chart being 1° of longitude to the inch. The meridians and parallels are to be drawn for every degree of longitude and latitude respectively.

The difference of longitude of the extreme meridians of the chart is 4°, and, since the scale of the chart is 1° of longitude to the inch, we draw a line 4 inches long at the bottom of the page, (Fig. 14), to represent the parallel of latitude of 54° N. Divide this line into four equal parts, and mark the left hand extremity 142° E., the right hand extremity 146° E., and the points of division as in the figure.

Through the extremities of this line, and the three points of division, erect perpendiculars to represent the meridians.

The distances between the various parallels of latitude are found as shown in the following tabular form :—

Latitude.	Mer. Parts.	*d*.m.p.	*d*.m.p. on chart.
°	Nautical Miles.	Nautical Miles.	Inches.
58	4294·30	111·68	1·86
57	4182·62	108·72	1·81
56	4073·90	105·93	1·76
55	3967·97	103·33	1·72
54	3864·64		

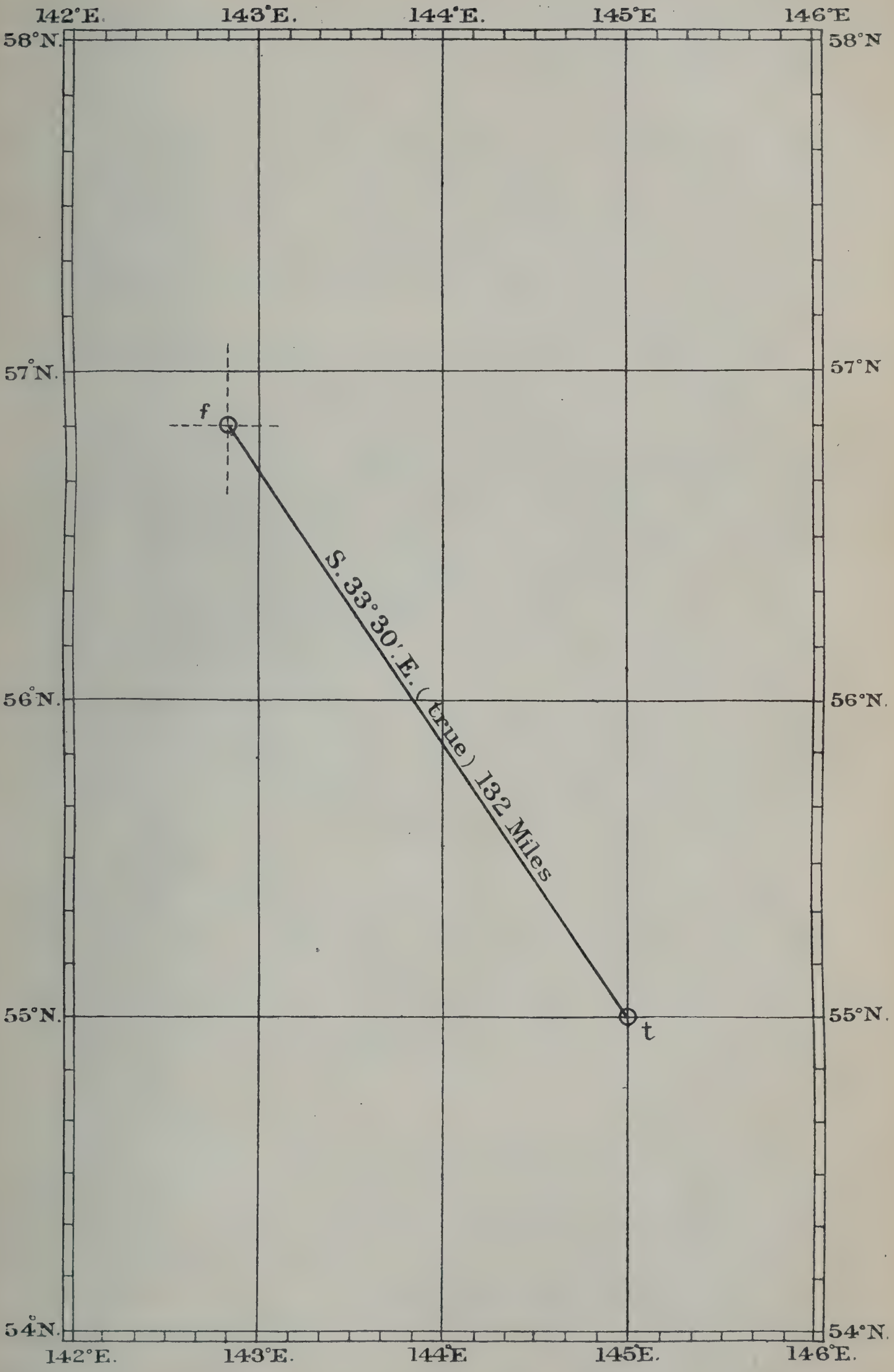

142°E.
143°E.
144°E.
145°E
146°E
58°N.
58°N
57°N.
57°N
56°N.
56°N.
55°N.
55°N.
54°N.
54°N.
142°E.
143°E.
144°E
145°E.
146°E.
f
t
S. 33° 30′ E. (true) 132 Miles

Fig. 14.

We now draw the parallels of latitude. The parallel of 55° is drawn at a distance of 1·72 inches from the line at the bottom of the page. The parallel of 56° is drawn at a distance of 1·76 inches from the parallel of 55°, and so on.

In order to be able to put down positions on the chart with accuracy, it is necessary to graduate the extreme parallels and meridians of the chart. The graduation of a parallel is the same as that of the equator, and simply consists of dividing the length representing degrees into a number of equal parts. The graduation of the meridian is effected by carrying still further the process of finding the positions on the chart of the parallels of latitude. In Fig. 14 the chart has been graduated for every 10′ of latitude and longitude.

22. Plotting positions on a Mercator's chart.—*Example.* Plot on the chart Fig. 14 a position *f* whose latitude is 56° 50′ N. and whose longitude is 142° 50′ E.

The position obviously falls within the rectangular area on the chart comprised between the parallels of 56° N. and 57° N. and between the meridians of 142° E. and 143° E., the nearest parallel being 57° N. and the nearest meridian 143° E., so that the position lies near to the N.E. corner of the rectangle.

Place the edge of the parallel rulers against the parallel of 57° N., move it until its edge passes through the graduation of 56° 50′ N. and then draw in a short line representing a portion of the parallel of 56° 50′ N. in the neighbourhood of the N.E. corner. Again, place the edge of the parallel rulers against the meridian of 143° E., move it until its edge passes through the graduation of 142° 50′ E. and then draw a short line representing a portion of the meridian of 142° 50′ E. in the neighbourhood of the N.E. corner. The intersection of these two short lines is the position on the chart required.

23. To find the compass course from one position to another.—Let *f* and *t* be the two positions on the chart. Join *ft* by a straight line, then we notice that the direction of *t* from *f* is between South and East (true). If we measure the angle which the line *ft* makes with the meridian, we find it to be 146° 30′, and consequently the true course from *F* to *T* is 146° 30′. We have now to find the compass course.

True course	146° 30′
	180 00
	S. 33 30 E.
Variation from variation chart	8 12 W.
Magnetic course	S. 25 18 E.
Deviation from deviation table	3 45 W.
Compass course	S. 21 33 E.

Therefore the compass course to steer is S. 21½° E.

On the majority of the published charts a diagram of a compass card is printed which gives magnetic and true directions for every degree. Fig. 15 shows such a compass card, the variation being 7° 40′ W.

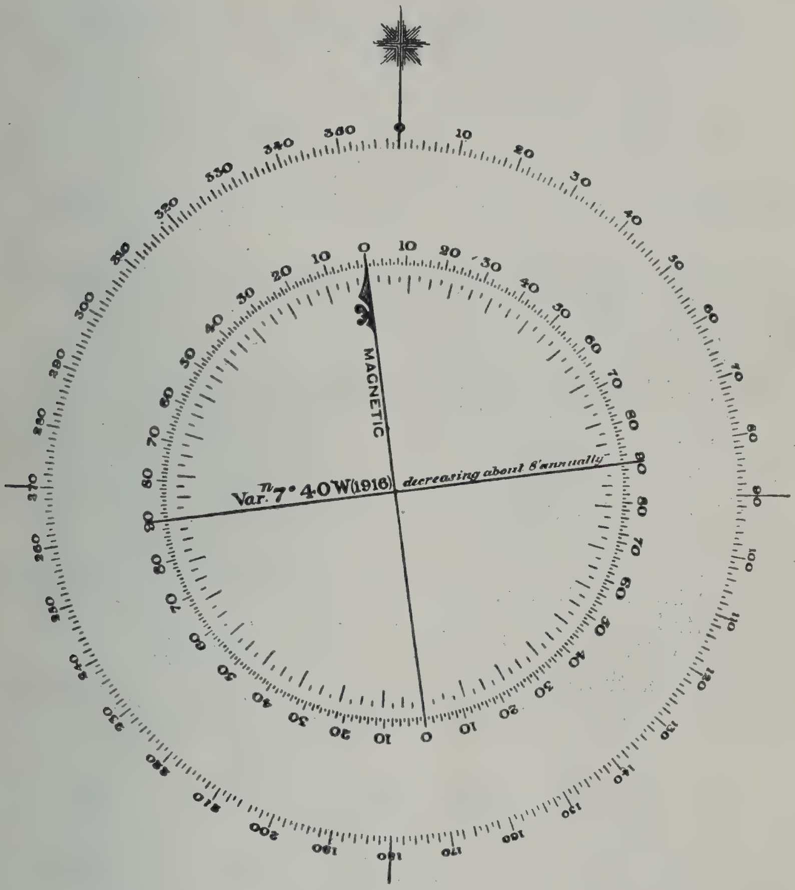


Fig. 15.

When such a compass is printed on the chart the magnetic course may be found by transferring the line *ft*, by means of the parallel rulers, to a position passing through the centre of the compass; the magnetic course may then be immediately read off. When using this method we must bear in mind that the variation changes slightly from year to year; consequently the information given on the engraved compass card should be examined and, if necessary, a correction made to any direction taken from it. For example, in Fig. 15, the variation is given as 7° 40′ W. (1916), decreasing about 8′ annually.

Course as taken from compass on chart -	S. 25° 45′ E.
Change in variation (1912 to 1916) -	32 W.
Magnetic course (1912) - - -	S. 25 13 E.
Deviation from deviation table - -	3 45 W.
Compass course - - - -	S. 21 28 E.

therefore the compass course to steer is S. 21°½ E. as before.

24. To find the distance from one position to another.

—Let the two positions on the Mercator's chart be *f* and *t* (Fig. 16). Let the parallel of latitude through *f* intersect the meridian through *t* in *m*. Let *F*, *T* and *M* be the points on the earth's surface represented by *f*, *t* and *m* on the chart, then the length of *FT* is the distance between the points represented by *f* and *t*, and *TM* is the difference of latitude between the same points and may be ascertained from the graduations at the side of the chart.

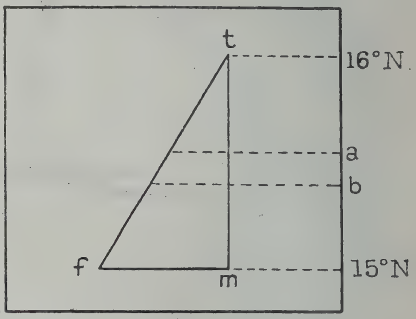


Fig. 16.

Now $\frac{FT}{TM} = \frac{ft}{tm}$ (§ 20); therefore *ft* represents the distance on the same scale as *tm* represents the known difference of latitude. Thus, if the latitudes of *F* and *T* are 15° N. and 16° N. respectively, and if the lengths of *ft* and *tm* on the chart are 3 and 1·5 inches respectively, the distance is 120 miles.

The degree of accuracy thus obtained is seldom necessary, and it is customary to take, on the dividers, the largest convenient length, say, that corresponding to a difference of latitude of 10′ (*ab* in Fig. 16) from the side of the chart, and from that part of the scale midway between the parallels of *F* and *T*, and to ascertain the number of miles represented by *ft* on the assumption that *ft* represents the distance on the same scale as *ab* represents 10 miles.

The latter method is sufficiently accurate for all practical purposes, provided the distance does not exceed 600 miles. For example, in latitude 60°, if we take for scale the length at the side of the chart which represents a difference of latitude of 10 miles, the error, provided that the dividers have been accurately set, will not exceed 1 per cent., when the distance is 600 miles and the mean latitude 60°.

Where the rhumb line crosses the equator we may still measure distances in this manner, but in all cases where great accuracy is required the distance should be found by calculation, as explained in the following chapter.

25. To allow for a current when finding the course.—When a ship's motion is influenced by currents or tidal streams, her direction of movement is not, in general, the same as that of the fore-and-aft line. The direction of the ship's track at any time is called the course made good, and the actual speed over the bottom of the sea in that direction is called the speed made good; the latter is often referred to as the speed over the ground, in distinction to the speed through the water.

The direction in which a current is running is called the set of the current, and the speed in knots at which it is running is called the drift of the current The set and drift of a current may be obtained from a chart called a current chart, and the direction and rate of a tidal stream from an atlas called a tidal atlas, as explained in Part III.

To find what course should be steered in order that the course made good should be as desired, the triangle of velocities is employed.

Example.—In § 23 the magnetic course has been found to be S. 25°¼ E. From the current chart it has been found that a current running S.S.W. (mag.) 2 knots will probably be experienced. It is required to find the compass course. From *f*, Fig. 17, lay off *fx* to represent S.S.W. 2 knots (the set and drift of the current expected) on any convenient scale. With centre *x* and radius *xy* to represent 10 knots (the ship's speed through the water on the same scale) describe a circle cutting *ft* in *y*; then the direction of *xy* which is S. 34° E. (mag.) gives the course in order to make good S. 25°¼ E. (mag.) on

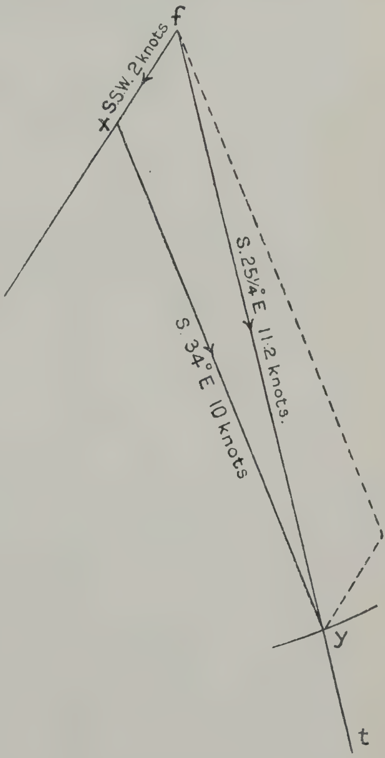


FIG. 17.

the assumption that the set and drift of the current is S.S.W. 2 knots.

Magnetic course - - - -	S. 34° E.
Deviation from deviation table - -	4° W.
Compass course - - - -	S. 30° E.

The speed made good along the line *ft* is given by the length *fy*. which represents a speed of 11·2 knots.

CHAPTER IV.

THE COURSE AND DISTANCE BY CALCULATION.

26. Fundamental formulæ for the rhumb line.—When great accuracy is required, the course and distance are found by calculation.

In Fig. 18 let FT be the rhumb line joining two places F and T. Between F and T let a large number (n) of equidistant parallels of latitude be drawn cutting the rhumb line in F, A, B, C, &c.

Let the meridians through these points intersect the equator in D, A', B', C', &c. and the parallels of latitude in X, Y, Z, &c., as in the figure.

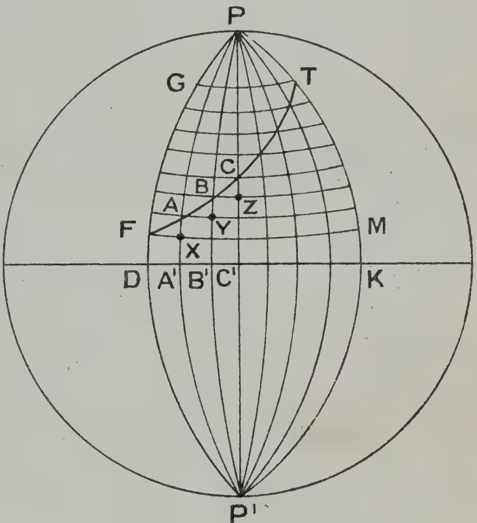


Fig. 18.

In the small triangles FAX, ABY, BCZ, &c., the angles FXA, AYB, BZC, &c., are right angles; the angles FAX, ABY, BCZ, &c., are all equal, each being equal to the course; also the sides AX, BY, CZ, &c., are all equal; therefore the triangles are equal in all respects, and, as they are very small, may be considered plane right angled triangles.

In the triangle FAX,

$$AX = FA \text{ cos course}$$
$$\therefore n\,.\,AX = n\,.\,FA \text{ cos course}$$
$$\therefore d \text{ Lat.} = \text{Distance cos course} \quad \ldots\ldots \quad (1)$$

Again

$$FX = FA \text{ sin course}$$
$$\therefore n\,.\,FX = n\,.\,FA \text{ sin course.}$$

Now $FX + AY + BZ +$ &c. is called the departure (Dep.) and is named East or West according as the d Long. is named East or West.

Since $FX = AY = BZ =$ &c., the departure $= n \cdot FX$.

$\therefore$ Departure $=$ distance sin course. . . . . (2)

Dividing equation (2) by the corresponding sides of equation (1), we have

$$\text{Tan course} = \frac{\text{departure}}{d\ \text{Lat.}} \quad \ldots\ldots\ldots\ldots \quad (3)$$

27. Formula for the departure.—In Fig. 18 let the latitudes of F and T be L and L' respectively and let the difference between the latitudes of adjacent parallels be dL, then we have

$$DA' = FX \sec L = \frac{\text{Dep.}}{n} \sec L$$

$$A'B' = AY \sec (L + dL) = \frac{\text{Dep.}}{n} \sec (L + dL)$$

$$B'C' = BZ \sec (L + 2dL) = \frac{\text{Dep.}}{n} \sec (L + 2dL)$$

and so on.

By addition we have, since $DA' + A'B' + B'C' +$ &c. is the d Long.,

d Long

$$= \frac{\text{Dep.}}{n}\Big[\sec L + \sec (L + dL) + \sec (L + 2dL) + \ldots + \sec (L' - dL)\Big]$$

$$= \frac{\text{Dep.}}{n}\Big[\sec 0 + \sec dL + \sec 2dL + \ldots + \sec (L' - dL)$$

$$- \sec 0 - \sec dL - \sec 2dL \ldots - \sec (L - dL)\Big]$$

Now

$$n \times R\, dL = d\ \text{Lat.} \qquad \therefore n = \frac{d\ \text{Lat.}}{R\, dL}$$

$$\therefore d\ \text{Long.} = \frac{\text{Dep.} \times R\, dL}{d\ \text{Lat.}}\Big[\sec 0 + \sec dL + \sec 2dL + \ldots + \sec (L' - dL)$$

$$- \sec 0 - \sec dL - \sec 2dL - \ldots - \sec (L - dL)\Big]$$

the product of $R\, dL$ and the difference of the two series within the brackets on the right is the difference of the meridional parts between F and T (§ 20).

Therefore

$$d\ \text{Long.} = \frac{\text{Dep.} \times d\text{.m.p.}}{d\ \text{Lat.}}$$

Or

$$\text{Dep.} = \frac{d\ \text{Long.} \times d\ \text{Lat.}}{d\text{.m.p.}} \quad \ldots\ldots\ldots\ldots \quad (4).$$

28. Formulæ for course and distance.—

From (3) and (4) we have

$$\text{Tan course} = \frac{d\ \text{Long}}{d\text{.m.p.}}$$

From (1) we have

$$\text{Distance} = d\,\text{Lat. sec Course.} \qquad \text{(A)}$$

When the *d* Long. is 0°, the course is 0°, and the distance is equal to the *d* Lat.

From (2) we have

$$\text{Distance} = \text{Dep. cosec Course.} \qquad \text{(B)}$$

When the *d* Lat. is 0°, the course is 90° and the distance is equal to the departure.

On account of the different rates at which the secants and cosecants of angles which are near 0° and 90° vary, it is advisable to find the distance from formula (B) when the course is very large.

Example:—Find the course and distance from Plymouth, Lat. 50° 20′ N., Long. 4° 9′ W., to Bermuda, Lat. 32° 19′ N., Long. 64° 49′ W.

Plymouth - - -	Lat. 50° 20′ N.	m.p. 3505·70	Long. 4° 09′ W.
Bermuda - - -	„ 32 19 N.	„ 2050·83	„ 64 49 W.
	18 01 S.	*d*.m.p. 1454·87	60 40 W.
	60		60
	d Lat. 1081′ S.		*d* Long. 3640′ W.

$$\tan \text{course} = \frac{d\,\text{Long.}}{d.\text{m.p.}} = \frac{3640}{1454\cdot87}$$

3640 log 3·56110

1454·87 log 3·16283

68° 12′·7 *L* tan 0·39827

Therefore, since the *d* Lat. is South and the *d* Long. is West, the course is S. 68° 12′·7 W.

Distance = *d* Lat. sec course = 1081 sec. 68° 12′·7

1081 log 3·03382

68° 12′·7 *L* sec 0·43043

2912 log 3·46425

Therefore the distance is 2,912 nautical miles.

29. Approximate formula for the departure.—We have from (4),

$$\text{Dep.} = \frac{d\,\text{Long.} \times d\,\text{Lat.}}{d.\text{m.p.}}$$

$$\therefore \text{Dep} = \frac{d\,\text{Long.} \times n.dl}{dl\,[\sec L + \sec(L+dL) + \sec(L+2\,dL) + \;.\;.\;.\;.\; + \sec(L'-dL)]}$$

$$= \frac{n.d\,\text{Long.}}{\sec.\,L + \sec(L+dL) + \sec(L+2\,dL) + \;.\;.\;.\;.\; + \sec(L'-dL)}$$

Now the series in the denominator on the right consists of *n* terms, the terms being the secants of *n* gradually increasing angles. If the secants of the angles increased at the same rate as the angles themselves, the series would be equal to n times the secant of the mean of the angles, that is, since dL is indefinitely small,

$$n \,.\, \sec \frac{L + L'}{2}$$

Now the secants increase faster than the angles themselves, so that, if we assume this value for the series, the smaller the number of terms in the series, the more correct our assumption will be; in other words, the smaller the d Lat. the more correct our assumption.

Again, while the secants of small and medium angles increase slowly, the secants of large angles increase very rapidly, so that the smaller the angles in the series—that is, the smaller the latitudes L and L', the more correct will be the assumption. Therefore, when the d Lat. is small, and when the latitudes are not very great, we have

$$\text{Dep.} = \frac{n.d \text{ Long.}}{n \sec \frac{L + L'}{2}}$$

$$= d \text{ Long.} \cos \frac{L + L'}{2}$$

Therefore, calling $\frac{L + L'}{2}$ the middle latitude, we have the approximate formula

$$\text{Dep.} = d \text{ Long.} \cos \text{Mid. Lat.} \quad . \quad . \quad . \quad . \quad (5).$$

In the above we have assumed that the two places are on the same side of the equator. When the two places are on opposite sides of the equator, we have

$$\text{Dep.} = \frac{d \text{ Long.} \times d \text{ Lat.}}{dl\,[\sec 0 + \sec dL + \,.\,.\, + \sec (L - dL) + \sec 0 + \sec dL + .\,. + \sec (L' - dL)].}$$

$$= \frac{d \text{ Long.} \times d \text{ Lat.}}{n.\, dl \sec \frac{L + 0}{2} + m.\, dl \sec \frac{L' + 0}{2}},$$

where n and m are the numbers of terms in the two series. Therefore if l is the linear latitude corresponding to L, and l' the linear latitude corresponding to L', we have

$$\text{Dep.} = \frac{d \text{ Long.} \times d \text{ Lat.}}{l \sec \frac{L}{2} + l' \sec \frac{L'}{2}}$$

Now, if neither L or L' is greater than 10°, we have approximately $\sec \frac{L}{2} = \sec \frac{L'}{2} = 1$, and the approximate formula for the departure, when F and T are on opposite sides of the equator, becomes

$$\text{Dep.} = d \text{ Long.} \quad . \quad . \quad . \quad . \quad (6).$$

30. Approximate method of finding the course and distance by the traverse table.—It will be noticed from (1), (2), and (3) that the *d* Lat., Dep. and distance may be regarded as the three sides of a plane right-angled triangle whose hypotenuse is the distance, the angle adjacent to the *d* Lat. and opposite to the departure being the course.

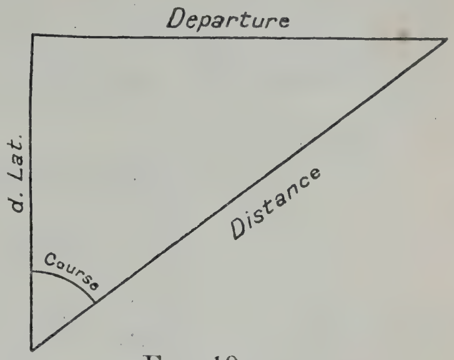
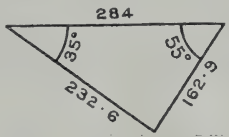


Fig. 19.

A table, called the traverse table, which merely consists of the solutions of a large number of plane right-angled triangles, has been constructed and is given in Inman's tables. The sides of the triangles are named as shown in Fig. 19.

The table gives the sides of right-angled triangles whose hypotenuses vary by unity from 1 to 600, and whose angles vary by 1° from 1° to 89°. The hypotenuses are shown at the top of the page and the angles at the sides. The arrangement of the table is such that the length of the side of the triangle adjacent to an angle is shown on that side of the column nearest to that angle, as will be seen by comparing the following extract from the traverse table with the triangle shown above it:—



Distance	. . . .	284		. . . .	. .
Co. . .	. . . .	Diff. Lat.	Dep.	. . . .	Co.
. . . .	. . . .	. .	. .	. . . .	. .
35 . .	. . . .	232·6	162·9	. . . .	55
. . . .	. . . .	. .	. .	. . . .	. .
Co. . .	. . . .	Dep.	Diff. Lat.	. . . .	Co.

The traverse table may be used for the solution of any formula which includes two lengths and a trigonometrical ratio.

We must be careful to remember that, under any particular hypotenuse, the number nearest an angle gives the side adjacent to that angle; for example, in the portion of the table shown above, 162·9 is the side adjacent to 55°, and therefore 232·6 is the side opposite to 55°. Again, 232·6 is the side adjacent to 35°, and therefore 162·9 is the side opposite to 35°.

Thus we see that

$$\frac{162\cdot9}{284} = \cos 55^\circ$$

$$\frac{232\cdot6}{284} = \sin 55^\circ.$$

$$\frac{232\cdot6}{162\cdot9} = \tan 55^\circ.$$

As an example, let us solve the equation

$$x = 284 \cos 55^\circ.$$

Entering the table with 284 as hypotenuse, the side adjacent to the angle 55° is 162·9; therefore x is 162·9.

It will now be seen that this table may be used for finding the departure when the *d* Long. and Mid. Lat. are given.

Example:—If the *d* Long. is 284′ and the Mid. Lat. 55°, we have (§ 29)

$$\begin{aligned}\text{Dep.} &= d\ \text{Long.} \cos \text{Mid. Lat.}\\ &= 284' \cos 55^\circ,\end{aligned}$$
and, using the table as shown above, we find that the departure is 162′·9.

We will now show by an example how the course and distance may be found by means of the traverse table.

Example:—Find the course and distance from *F* Lat. 56° 50′ N., Long. 142° 50′ E. to *T* Lat. 55° 00′ N., Long. 145° 00′ E.

F Lat. 56° 50′ N.	Lat. 56° 50′ N.	Long. 142° 50′ E.
T ,, 55° 00′ N.	,, 55° 00′ N.	,, 145° 00′ E.
1 50 S.	2/111 50	2 10 E.
60		60
	Mid. Lat. 55 55 N.	
d Lat. 110′ S.		*d* Long. 130′ E.

$$\begin{aligned}\text{Dep.} &= d\ \text{Long.} \cos \text{Mid. Lat.},\\ &= 130' \cos 55^\circ\ 55' = 72'\cdot8 \text{ by traverse table.}\end{aligned}$$

$$\text{Tan Co} = \frac{\text{Dep.}}{d\ \text{Lat.}} = \frac{72\cdot8}{110}$$

Searching the tables till we find 72·8 as Dep. corresponding to 110 as *d* Lat, the course and distance will be found to be

S 33°½ E., 132 miles.

CHAPTER V.

THE GREAT CIRCLE TRACK.

31. The gnomonic chart.—In § 18 it was remarked that the shortest distance between two places is along the arc of the great circle which joins them. When a saving of time is a prime consideration, it is necessary to find how a ship should be steered in order that her track may coincide as far as possible with the great circle arc. To do this it is necessary to lay down the great circle arc on the Mercator's chart, and this is easily done by the aid of charts constructed on the gnomonic projection. On these charts great circles are represented by straight lines, and therefore they show at a glance whether the great circle track leads the ship into any danger.

The gnomonic chart is constructed on the following principle—Every point of half the surface of the earth is projected from the centre on to a tangent plane at some selected point, called the point of contact.

The plane of the equator contains the earth's centre, and, therefore the equator, when projected from the centre on to a tangent plane, becomes a straight line. Similarly, the meridians become straight lines converging to that point which is the projection of the pole; and every great circle of the earth becomes a straight line.

The planes of the parallels of latitude do not contain the earth's centre; therefore parallels of latitude when projected on to the tangent plane become curves, which are sections of cones.

In Fig. 20, let a tangent plane YZ touch the earth at the point of contact C whose latitude is L_C, and let us consider the projection of meridians, parallels, &c., on this tangent plane.

Let eq be the projection of an arc of the equator EQ, and p be the projection of the pole P: then pCq is the projection of the meridian of C, and is called the central meridian of the chart.

Let L_A and L_B be the latitudes of two points A and B on the central meridian, and situated on either side of the point of contact C. Let a and b be the projections of A and B on the tangent plane.

To find ab.

We have

$$ab = aC + Cb = OC \tan aOC + OC \tan bOC.$$

Now $OC = R$, the radius of the earth,

$$aOC = qOC - qOA = L_C - L_A,$$

and

$$bOC = qOB - qOC = L_B - L_C.$$

$$\therefore ab = R \tan (L_C - L_A) + R \tan (L_B - L_C) \qquad (1)$$

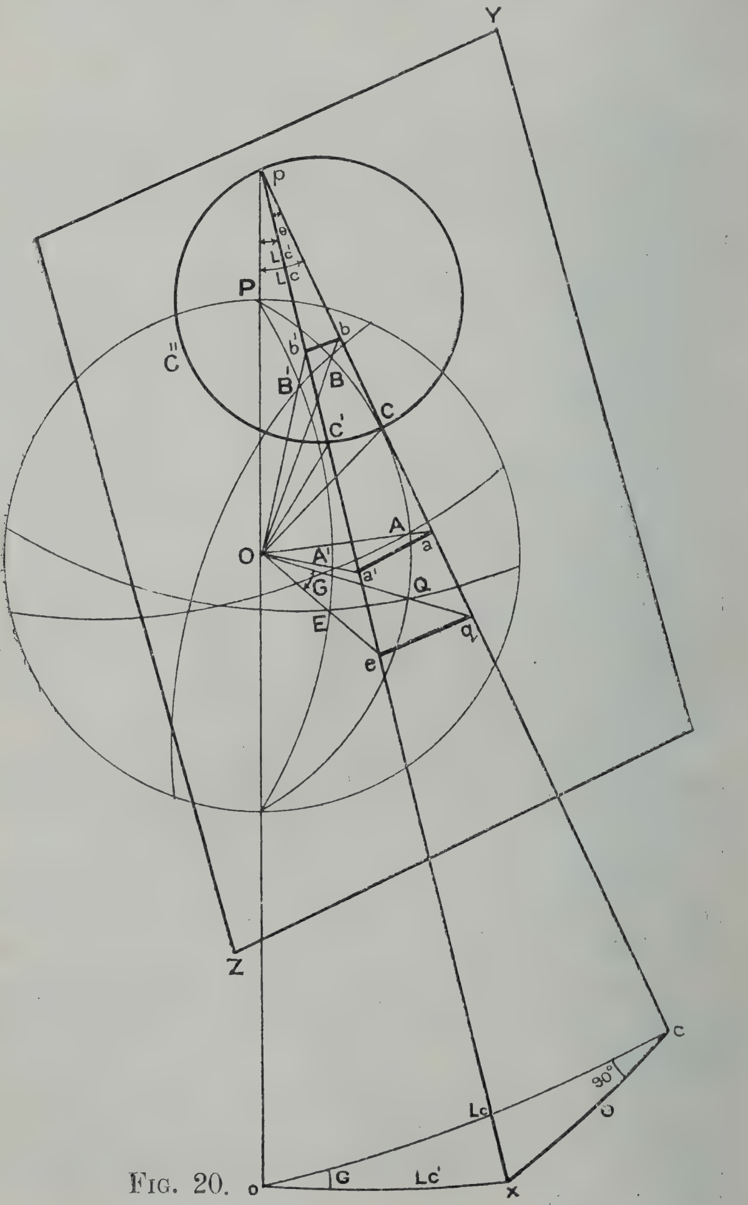


FIG. 20.

Let us now consider the projection of a meridian $A'B'$ whose longitude differs from that of the central meridian by G.

Let great circles be drawn through B and A intersecting the central meridian at right angles and the meridian $B'A'$ in the points B' and A'. Let the projections of these great circles be the straight lines bb' and aa' respectively. Since the great circles BB' and AA' are perpendicular to the central meridian, the lines aa' and bb' are perpendicular to ab.

To find aa' and bb'.

With centre p, describe a sphere of any radius to cut the lines pa, pa', and pO in the points c, x, o respectively; then the spherical triangle cxo is right-angled at c, since the plane pxc is perpendicular to the plane poc. The angle xoc being the angle between the planes of the two meridians is equal to their difference of longitude G. The side oc is equal to the angle opc, which is equal to $90° - pOC$ since pCO is a right angle; therefore oc is equal to the angle COQ = latitude of $C = L_C$.

Let the angle xpc be θ, then the side xc of the spherical triangle is also θ.

In the right-angled spherical triangle oxc we have,

$$\sin L_C = \tan \theta \cot G,$$

$$\therefore \tan \theta = \sin L_C \tan G.$$

In the plane right-angled triangle paa'

$$aa' = ap \tan \theta = (aC + Cp) \tan\theta$$

$$\text{Now } aC + Cp = OC \tan aOC + OC \tan pOC$$

$$= R \tan (L_C - L_A) + R \cot L_C,$$

$$\therefore aa' = R\Big[\tan (L_C - L_A) + \cot L_C\Big] \sin L_C \tan G$$

or, in a form adapted to logarithms,

$$aa' = R \cos L_A \sec (L_C - L_A) \tan G \quad - \quad - \quad (2)$$

$$\text{Similarly, } bb' = R \cos L_B \sec (L_B - L_C) \tan G \quad - \quad - \quad (3)$$

Let us now consider the projection of the parallel of latitude L_D. To do this it is necessary to fix, on the projections of the meridians, the projections of all points whose latitude is L_D.

Let a circle $CC'\,C''$ described on pC as diameter intersect the projections of the meridians in a series of points $C,'C''$, &c.; then the projections of the points of the parallel of latitude L_D are placed on the projections of the meridians by reference to the points C, C', C'', &c.

To place the point C′, C″, &c., on the projections of the meridians.

The circle $CC'\ C''$ is described on pC as diameter; therefore, the angle $CC'p$ being the angle in a semicircle is a right-angle; therefore, the points C', C'' &c., are the feet of the perpendiculars dropped from the point of contact C on to the projections of the meridians.

Let the projection of the parallel of latitude L_D intersect the various meridians in d, d', d'', &c., as shown in Fig. 21.

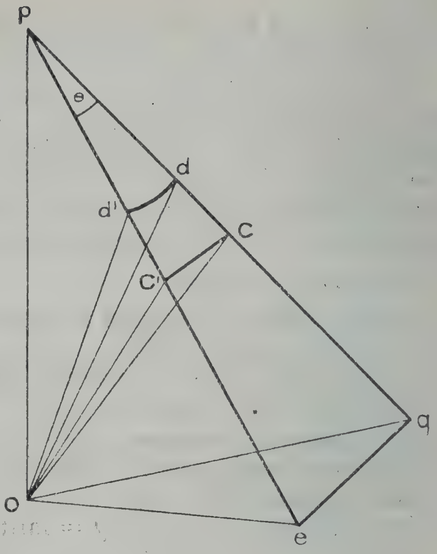


FIG. 21.

To find the length Cd.

In the triangle dOC we have

$$dC = OC \tan dOC = OC \tan (dOq - COq)$$
$$= R \tan (L_D - L_C). \quad - \quad - \quad - \quad - \quad - \quad (4)$$

To find the length C′d′.

Remembering that OCC' and $CC'p$ are right angles, we have

$$OC'^2 = OC^2 + CC'^2 = (Op^2 - pC^2) + (pC^2 - pC'^2).$$
$$\therefore OC'^2 = Op^2 - pC'^2,$$

from which it follows that the angle $OC'p$ is a right angle, and consequently the angle OpC' is the latitude of $C' = L_C'$.

Now in the triangle $OC'd'$ we have

$$C'd' = OC' \tan d'OC' = OC' \tan (L_D - L_C').$$

Also in the triangle OpC'

$$OC' = Op \sin OpC' = Op \sin L_C',$$

and in the triangle pCO

$$Op = OC \operatorname{cosec} OpC = R \operatorname{cosec} L_C.$$

Therefore $OC' = R \operatorname{cosec} L_C \sin L_C'$.

Therefore $C'd' = R \operatorname{cosec} L_C \sin L_C' \tan (L_D - L_C')$.

Now the side ox of the spherical triangle ocx (Fig. 20) is equal to the angle $opx = L_C'$.

Therefore $\cos G = \tan L_C \cot L_C'$, or $\tan L_C' = \tan L_C \sec G$.

Therefore to find $C'd'$ we have the formulæ

$$\left.\begin{array}{l} C'd' = R \operatorname{cosec} L_C \sin L_C' \tan (L_D - L_C') \\ \text{where } \tan L_C' = \tan L_C \sec G \end{array}\right\} \quad - \quad - \quad (5)$$

When L_D is greater than L_C', $C'd'$ should be laid off towards the pole, and, when less, towards the equator.

At the point of contact, angles on the earth's surface are correctly represented on the chart; when the angle, between a great circle through the point of contact and a great circle which does not pass through the point of contact, is a right angle, this angle is correctly represented; with these exceptions, angles on the earth's surface are not correctly represented.

32. Special cases of the gnomonic chart.—When the point of contact is at either pole, the meridians are projected as straight lines radiating from the point of contact, the angle between any two lines being equal to the *d*Long of the meridians of which they are the projections. The parallels of latitude are projected into a system of concentric circles, the centre being the pole. The radius of the parallel of latitude L_D is R cot L_D.

When the point of contact is on the equator, the meridians are projected into a system of parallel straight lines; the equator is projected into a straight line perpendicular to the meridians; the parallels of latitude are projected into hyperbolas.

From formula (2), or by drawing a figure, we see that the distance of any meridian from the meridian through the point of contact is R tan G.

From formula (5), or by drawing a figure, we find that the distance from the equator of a point on the parallel of latitude L_D, is R sec G tan L_D.

33. Construction of a gnomonic chart.—The formulæ (1), (2), (3), (4) and (5) all involve one linear measurement, namely the radius of the earth R, so that the size of the chart depends on the length which we assign to R. To determine this we must take into consideration the height of the sheet of paper at our disposal, which we will suppose to be h inches, so that the length ab on the chart is h inches.

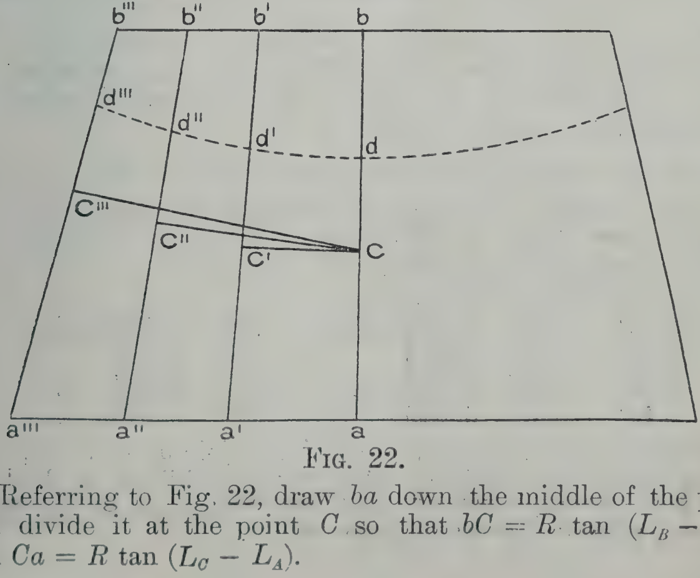


FIG. 22.

Referring to Fig. 22, draw ba down the middle of the page and divide it at the point C so that $bC = R \tan (L_B - L_C)$, and $Ca = R \tan (L_C - L_A)$.

Through a and b draw two lines at right angles to ab.

From formula (1) we have, since ab is represented by h inches on the chart,

$$R = \frac{h \text{ inches}}{\tan (L_C - L_A) + \tan (L_B - L_C)},$$

and this gives the value of R which is to be used in formulæ (2), (3), (4) and (5).

From a, lay off aa' as calculated from (2), and from b lay off bb' as calculated from (3).

Join $a'b'$; then $a'b'$ represents the meridian whose longitude differs from that of ab by G. In the same way another meridian $a''b''$ can be drawn whose longitude differs from that of ab by $2G$, and so on.

From C drop perpendiculars CC', CC'', &c., on to the meridians.

To draw the parallel of latitude L_D lay off Cd as calculated from (4). From C' lay off $C'd'$ as calculated from (5). From C'' lay off $C''d''$ as calculated from (5), and so on. Through the points d, d' d'', &c., draw a curve; then this curve will represent the parallel of latitude L_D. In the same way any other parallel may be drawn.

As an example of the above, let us construct a gnomonic chart on a page of this volume. The central meridian of the chart is to extend from lat. 30° S. to lat. 60° S., and include as many meridians (10° apart) as possible. The point of contact of the chart is to be in lat. 45° S., and the longitude of the central meridian is to be 120° W.

By formula (1) and considering the size of the page available (Fig. 23), we find that a value of 8 inches for R will be suitable, and we shall therefore construct the chart on the scale $R =$ 8 inches.

Formula (1) gives $ab = 4{\cdot}288$ inches. Draw a line ab, 4·288 inches long, down the middle of the page, as shown in Fig. 23. Since $(L_B - L_C) = (L_C - L_A)$ the point of contact C is at the middle point of the line ab.

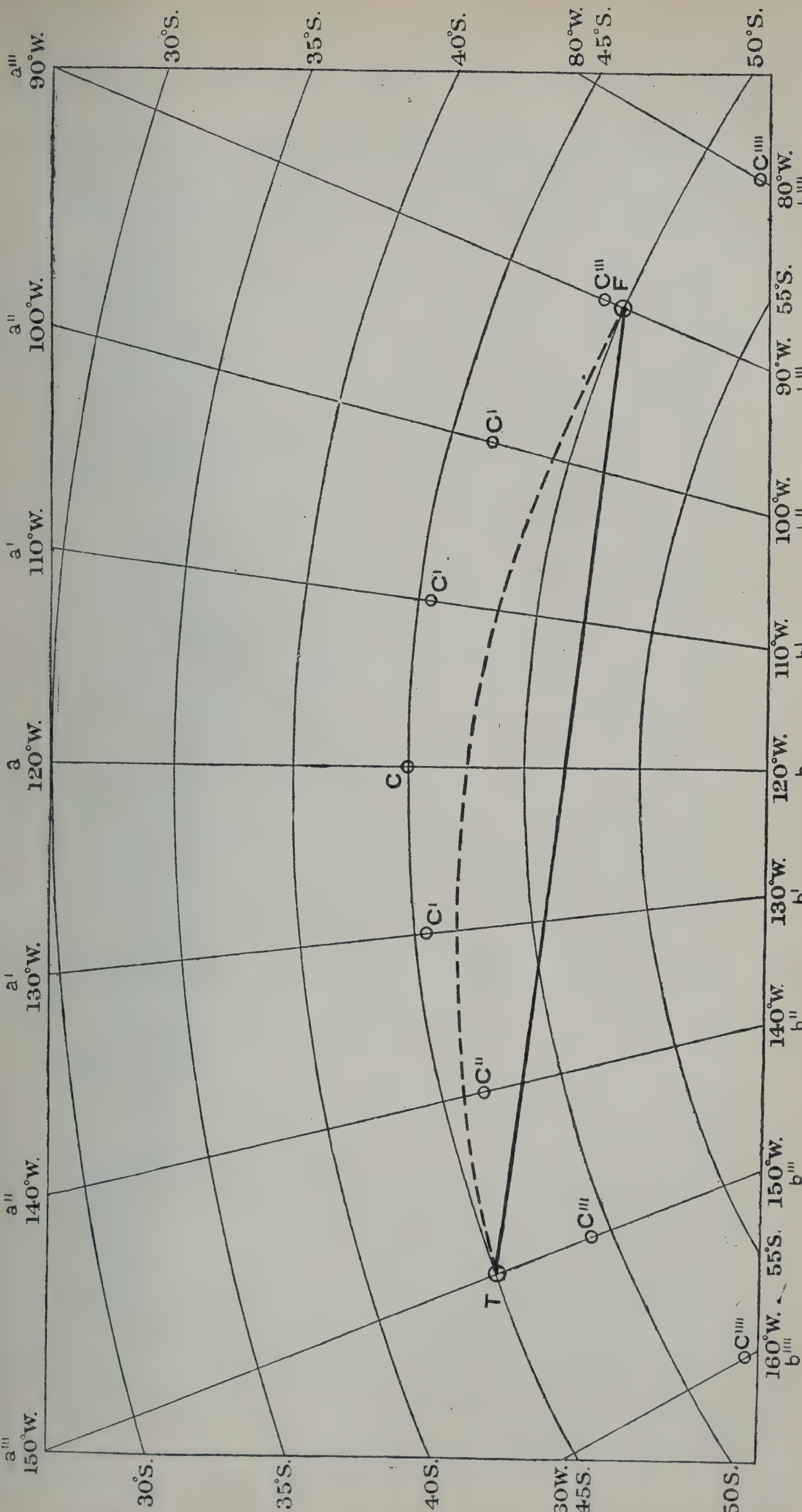
Through a and b draw lines at right angles to ab.

From formulæ (2) and (3) calculate aa', bb', aa'', bb'', &c., giving G the values 10°, 20°, 30° and 40°, so as to be able to draw in the meridians for every 10° of longitude.

The results are as follows:—

G 10°	aa' 1·265 inches	bb'	·730 inches.
G 20°	aa'' 2·610 ,,	bb''	1·507 ,,
G 30°	aa''' 4·140 ,,	bb'''	2·391 ,,
G 40°	aa'''' 6·018 ,,	bb''''	3·475 ,,

Having laid off the points a', b', &c., join a' b', a'' b'', &c., and so obtain the meridians. Mark these meridians, on the left, 130° W., 140° W., 150° W., and 160° W.; and on the right 110° W., 100° W., 90° W., and 80° W.


a'''
90°W.
30°S.
35°S.
40°S.
80°W.
45°S.
50°S.
a''
100°W.
a'
110°W.
a
120°W.
a'
130°W.
a''
140°W.
a'''
150°W.
C''''
80°W.
b''''
C'''
F
55°S.
90°W.
b'''
C''
100°W.
b''
C'
110°W.
b'
C
120°W.
b
C'
130°W.
b'
140°W.
b''
C''
150°W.
b'''
C'''
55°S.
T
160°W.
b''''
C''''
30°S.
35°S.
40S.
160W.
45S.
50S.

From the point of contact C drop perpendiculars on the various meridians and so find the points C', C'', &c.

Calculate the latitudes of the points C', C'', &c., by the second formula of (5), and these will be found to be as follows :—

C'	C''	C'''	C''''
45° 26′	46° 47′	49° 06′	52° 32′

We shall now draw in the parallels of latitude of 30° S., 35° S., 40° S., 45° S., 50° S., and 55° S.

First, find the distances from the point of contact C of these parallels by formula 4. Next, find the distances of the parallels of latitude from C', C'', &c., by the first formula of (5), and we find the various values to be as follows :—

Inches.	$C\,d.$	$C'\,d'$	$C''\,d''$	$C'''\,d'''$	$C''''\,d''''$
L_D 30°	2·144	2·224	2·487	2·961	—
L_D 35°	1·408	1·484	1·720	2·148	—
L_D 40°	·704	·767	·981	1·370	—
L_D 45°	—	·061	·245	·613	1·187
L_D 50°	·704	·625	·463	·134	·397
L_D 55°	1·408	1·358	1·191	·884	—

Plot the positions of d, d', d'', &c., for the various parallels of latitude, and draw curves through them, as shown in Fig. 23; mark the curves 30° S., 35° S., 40° S., 45° S., 50° S., and 55° S.

The chart is bounded on the right and left by drawing lines parallel to the central meridian.

34. To draw the great circle track on the Mercator's chart.—To draw the great circle track between two places f and t on the Mercator's chart, first draw it on the gnomonic chart as shown in Fig. 23, and note the latitudes of the points where the track crosses various meridians. These points should then be plotted on the Mercator's chart by means of their latitudes and longitudes, and a smooth curve drawn through them. In Fig. 24 the curve in full line shows the great circle track on the Mercator's chart, and the pecked lines in Figs. 23 and 24 show the rhumb line. The rhumb line lies on the equatorial side of the great circle track, unless it coincides with the equator or a meridian.

As it is impossible to steer along a great circle because it would necessitate continual alterations of course, points must be selected at convenient distances apart along the great circle track, and the ship must be steered from one to the other along the rhumb lines joining them. The closer these points are to one another, the more nearly will the track of the ship coincide with the great circle.

To estimate the distance required to be steamed in proceeding along the great circle in this approximate manner we have to find the sum of the distances along the several rhumb lines joining the points. As an example, suppose that it is required to steam along the great circle track from *F*, Lat. 50° S., Long. 90° W., to *T*, Lat. 45° S., Long. 150° W., and that we have to find the course to steer from *F* and the distance saved by proceeding along the approximate great circle track instead of the rhumb line.

Put down the points *F* and *T* on the gnomonic chart; the straight line joining them represents the great circle track on this chart. We have to transfer this line to the Mercator's chart, shown in Fig. 24, and to do this we transfer a number of points on the line *FT*, Fig. 23, to the Mercator's chart, the points so transferred being sufficiently close together to enable us to draw a smooth curve through them.

In this example we have noted the latitudes where *FT* cuts the meridians of 100° W., 110° W., &c., and they are as follows :—

Meridians -	100° W.	110° W.	120° W.	130° W.	140° W.
Latitudes -	51° 27′	52° 00′	51° 41′	50° 30′	48° 20′

Plot these latitudes on the corresponding meridians of the Mercator's chart (Fig. 24), and draw a smooth curve through them and through the points *f* and *t*. This curve represents the great circle track on the Mercator's chart.

To find the first course to steer and the total distance, we employ the approximate method explained in § 30 and find the courses and distances along the rhumb lines joining successive points. The first of these courses will be the course to steer from *F*, and the sum of the distances will be the distance steamed in proceeding from *F* to *T*.

The work is as follows, the *d.* Long. made on each rhumb line being 600′ :—

Lats.	Mid.Lat.	*d.* Lat.	Dep.	Course.	Distance.
50° 00′S.					
51 27	50°43′	87′	380′	S. 77° W.	390′
52 00	51 43	33	372	—	381
51 41	51 50	19	371	—	371
50 30	51 05	71	377	—	384
48 20	49 25	130	390	—	412
45 00	46 40	200	412	—	458
		Total distance - -			2396
The course and distance (found by the exact formulæ) along the rhumb line *f t* are - - -				N. 83° W.	2450
		Distance saved - -			54 miles.

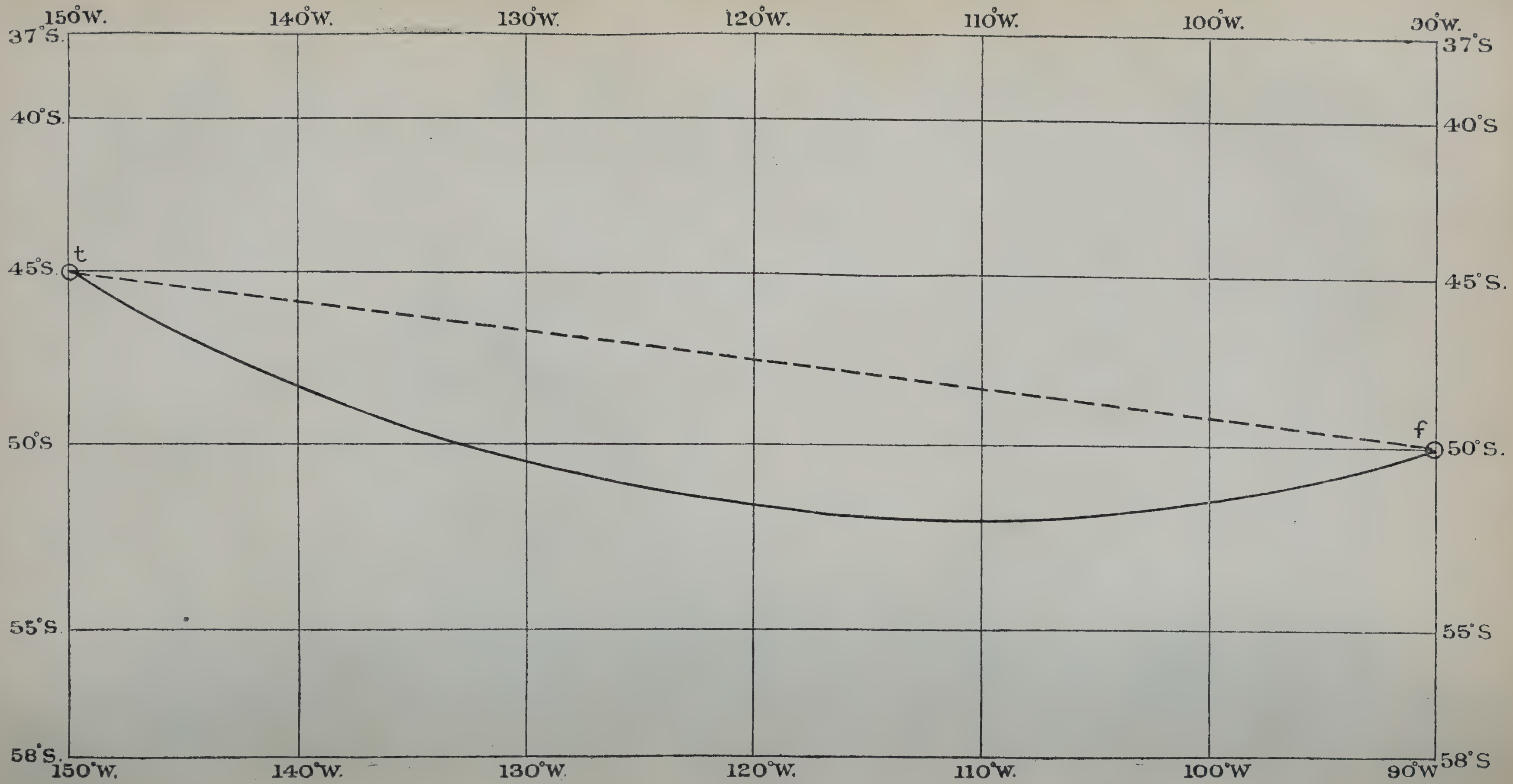

150°W.
140°W.
130°W.
120°W.
110°W.
100°W.
90°W.
37°S.
40°S.
45°S.
50°S.
55°S.
58°S.
37°S
40°S
45°S.
50°S.
55°S
58°S
t
f
150°W.
140°W.
130°W.
120°W.
110°W.
100°W
90°W

FIG. 24.

It should be noticed that, in considering the great circle track of the ship, we are concerned with the first course only, that is, the course to be steered from the place of departure *F*. The other courses are of little importance, because it is probable that observations will show that the ship has not made good the course steered, in which case a second great circle track should be laid down from the observed position of the ship and a new course determined on which to steer. If observations show that the ship has been set off the great circle, it is inadvisable to attempt to regain the original track.

35. Great circle track by calculation.—When a gnomonic chart is not available, the series of points with which to plot the great circle on the Mercator's chart may be found by calculation, but under these circumstances we cannot tell whether the great circle track will lead the ship into danger till the points have been plotted on the Mercator's chart. The method of calculation will be best shown by calculating the latitudes of the points in the foregoing example.

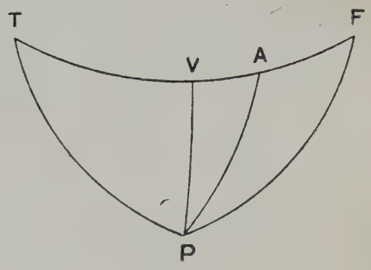


Fig. 25.

In Fig. 25 let *P* be the pole of the earth, and *F* and *T* the two places. Then in the spherical triangle *FPT*, *PF* is the co-Lat. of *F*, = 90° − 50° = 40°. Similarly *PT* is the co-Lat. of *T* = 45°. The difference of longitude between *F* and *T* is 60° W.; therefore the angle *P* is 60°.

Having the two sides *PF* and *PT* and the included angle *FPT* the side *FT* is found by the formula

$$\text{hav } FT = \text{hav } (PT - PF) + \text{hav } \theta,$$

$$\text{where hav } \theta = \sin PF \sin PT \text{ hav } P.$$

PF 40° L sin	9·80807
PT 45° L sin	9·84949
P 60° L hav	9·39794
L hav θ	9·05550
Nat hav θ	·11363
Nat hav ($PT-PF$) (5°)	·00190
Nat hav FT	·11553

$$FT = 39° \, 44'·5,$$

from which we see that the distance along the great circle arc from *F* to *T* is 2,384·5 miles.

Having the three sides of the spherical triangle PFT, we now find the angle F by the formula

$$\text{hav}\, F = \text{cosec}\, PF\, \text{cosec}\, PT \sqrt{\text{hav}\,(PT + TF - PF)\, \text{hav}\,(PT - TF + PF)}$$

PF	40° 00′	L cosec 10·19193
FT	39 44·5	L cosec 10·19427
$PF - FT$	0 15·5	
PT	45 00	
$PT + FT - PF$	44 44·5	$\frac{1}{2}L$ hav 4·58047
$PT + PF - FT$	45 15·5	$\frac{1}{2}L$ hav 4·58520
		L hav F 9·55187
		F = 73° 18′·2

We have now to find in what latitudes the great circle arc FT cuts the meridians of 100° W., 110° W., &c.

Let PV be the meridian which cuts FT at 90°; it is first required to find the angle VPF and the side PV.

In the right-angled spherical triangle PVF

$$\tan P = \cot F \sec PF, \text{ and } \sin PV = \sin PF \sin F.$$

F	73° 18′·2	L cot 9·47705	L sin 9·98132
PF	40° 00′	L sec 10·11575	L sin 9·80807
		L tan P 9·59280	L sin PV 9·78939
		P = 21° 23′	PV = 38° 00′,
			Lat V = 52° 00′.

Let the meridian of 100° W. intersect the great circle arc FT in A; then in the right-angled triangle PVA we have

$$VPA = VPF - APF = 21° 23' - 10° 00' = 11° 23'.$$

$$\text{Also } PV = 38° 00'.$$

$$\text{Now} \quad \tan PA = \tan PV \sec VPA.$$

$$\therefore \cot \text{Lat. of } A = \tan 38° \sec 11° 23'.$$

Similarly for the meridian of 110° W. we have

$$\cot \text{Lat. of } A' = \tan 38 \sec 1° 23'$$

and for the meridian of 120° W. we have

$$\cot \text{Lat. of } A'' = \tan 38° \sec 8° 37'$$

and so on. The calculations are shown below :—

Longs. *VPA.*	100° W. 11° 23′.	110° W. 1° 23′.	120° W. 8° 37′.	130° W. 18° 37′.	140° W. 28° 37′.
	9·89281 10·00863	9·89281 10·00013	9·89281 10·00493	9·89281 10·02334	9·89281 10·05658
Lats.	9·90144 51° 27′	9·89294 52° 00′	9·89774 51° 41′	9·91615 50° 30′	9·94939 48° 20′

Having obtained these latitudes, the curve is plotted on the Mercator's chart; the course to steer and the total distance are found in the manner explained in the preceding article.

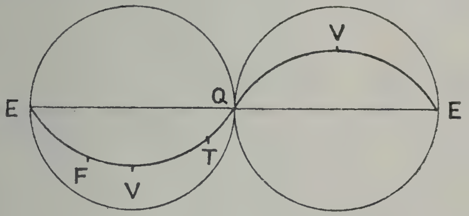
36. Great circle track by Towson's tables.—The points on the great circle track which have to be transferred to the Mercator's chart may be easily found by aid of Towson's Great Circle Tables and Linear Index, which are supplied to all H.M. ships with the chart set. The instructions for using them are bound up with the tables and should be carefully studied. When obtaining the points by these tables, it is recommended to draw figures as shown in the four following examples.

Since any two great circles bisect one another, the great circle through *F* and *T* is bisected by the equator at two points, *Q* and *E*. The figures show the whole of the great circle *FT* and the whole of the equator.

Example (1):—

F Lat. 50° 00′ S. *T* Lat. 45° 00′ S.
Long. 90° 00′ W. Long. 150° 00′ W., *d*.Long. 60° W.

From Index the Lat. of vertex is 52°. Long. from vertex, 21° 23′.



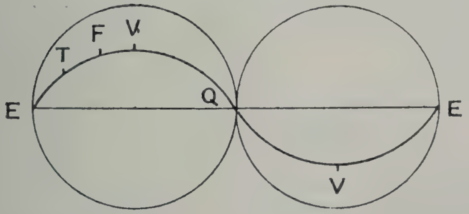
"Meridian in."

Fig. 26.

Longs.	90° 00′	100° 00′	110° 00′	120° 00′	130° 00′	140° 00′	150° 00′
Longs. from vertex	21 23	11 23	1 23	8 37	18 37	28 37	38 37
Lats. from tables	50 00	51 27	52 00	51 41	50 30	48 20	45 00

Example (2):—

F Lat. 54° 00′ N. *T* Lat. 30° 00′ N.
Long. 10° 00′ W. Long. 60° 00′ W., *d*.Long. 50° W.
Lat. of vertex, 55° 00′ N. Long. from vertex, 16° 00′.



"Both out."

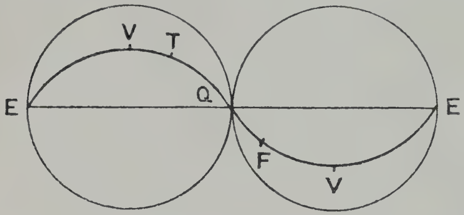
Fig. 27.

Longs.	10° 00′	20° 00′	30° 00′	40° 00′	50° 00′	60° 00′
Longs. from vertex	16 00	26 00	36 00	46 00	56 00	66 00
Lats.	54 00	52 04	49 03	44 48	38 38	30 00

Example (3):—

F Lat. 15° 45′ S. *T* Lat. 32° 19′ N.
Long. 6° 00′ W. Long. 64° 00′ W., *d*.Long. 58° W.

Lat. of vertex, 44° 00′. Long. from vertex, 73° 00′.



“ Equator in.”

Fig. 28.

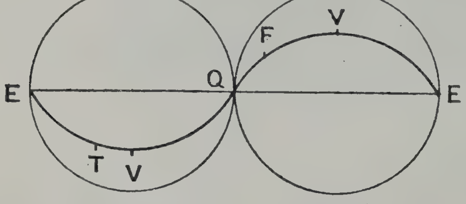
Longs. - -	6° 00′	15° 00′	25° 00′	35° 00′	45° 00′	55° 00′	64° 00′
Longs. from vertex.	73 00	82 00	88 00	78 00	68 00	58 00	49 00
Lats. - -	S. 15 45	S. 7 41	N. 1 56	N. 11 22	N. 19 53	N. 27 05	N. 32 19

Example (4):—

F Lat. 8° 55′ N. *T* Lat. 33° 37′ S.
Long. 79° 00′ W. Long. 151° 00′ E., *d*.Long. 130° 00′ W.

Lat. of vertex, 37° 00′. Long. from vertex, 78° 00′.

Longs. -	79° 00′	80° 00′	90° 00′	100° 00′	110° 00′	120° 00′	130° 00′	40° 00′
Longs. from vertex.	78 00	79 00	89 00	81 00	71 00	61 00	51 00	41 00
Lats. -	N. 8 55	N. 8 13	N. 0 46	S. 6 46	S. 13 46	S. 20 04	S. 25 22	S. 29 38



“ Both in.”

Fig. 29.

Longs. - -	150° 00′	160° 00′	170° 00′	180° 00′	170° 00′	160° 00′	151° 00′
Longs. from vertex.	31 00	21 00	11 00	1 00	9 00	19 00	28 00
Lats. - -	S. 32 51	S. 35 08	S. 36 29	S. 36 59	S. 36 40	S. 35 28	S. 33 37

In Towson's tables, the column headed "course" gives the angle *PFT* of the spherical triangle shown in Fig. 25, and this must not be confused with the course to be steered. The column headed "distance," gives the distance in miles from the nearest vertex, measured along the great circle *FT*.

37. The composite track.—When the vertex lies between the two places *F* and *T*, the great circle track takes the ship into a higher latitude than that of *F* or *T*, and in many cases takes the ship into a higher latitude than is desirable on account of the ice and bad weather likely to be encountered. Under these circumstances we have to determine the shortest track which does not cross a particular parallel of latitude. This problem will be easily understood by considering the following :—

In Fig. 30, let *A* and *B* be two points on a line which cuts the circle *C*; it is required to find the shortest route between *A* and *B* without going inside the circle, the points and the circle being in the same plane.

From *A* and *B* draw tangents to the circle, touching it at *D* and *E*; then the shortest route will be along the tangent *AD*, then along the circular arc *DE*, and then along the tangent *EB*.

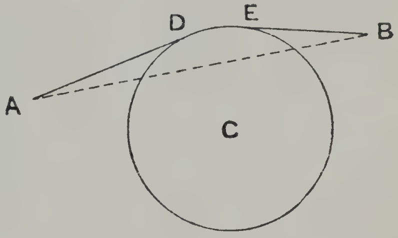


FIG. 30.

Similarly, if it is desired to steam from *F* to *T* by the shortest route without crossing a certain parallel of latitude, great circle arcs are drawn from *F* and *T*, Fig. 31, to touch the parallel of latitude at *D* and *E*. The track to be followed is the great circle arc *FD*, the arc of the parallel *DE* and the great circle arc *ET*. This track is called the composite track between *F* and *T*. It is easily determined, if a gnomonic chart is available, by drawing straight lines from *F* and *T* to touch the limiting parallel of latitude at points *D* and *E*. The points on the great circle arcs *FD* and *ET* are plotted on the Mercator's chart as shown above, the course to steer along the parallel *DE* is either East or West.

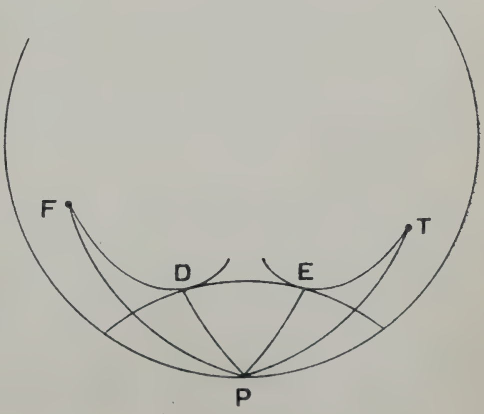


FIG. 31.

We will now show, by an example, how the longitude of the two points D and E on the limiting parallel may be found by calculation.

It is desired to steam by the shortest route from F, Lat. 29° 53′ S., Long. 31° 04′ E., to T, Lat. 34° 48′ S., Long. 138° 31′ E., without crossing the parallel of latitude of 42° S.

In the right-angled triangle PDF

$$\cos FPD = \tan PD \cot PF = \cot \text{Lat. of } D \tan \text{Lat. of } F.$$

In the right-angled triangle PET

$$\cos EPT = \tan PE \cot PT = \cot \text{Lat. of } E \tan \text{Lat of } T.$$

L cot 42° 00′ -	10·04556	L cot 42° 00′ -	10·04556
L tan 29 53 -	9·75939	L tan 34 48 -	9·84200
L cos FPD -	9·80496	L cos EPT -	9·88756
FPD =	50° 20′	EPT =	39° 28′
Long. F -	31 04 E.	Long. T -	138 31 E.
Long. D -	81 24 E.	Long. E -	99 03 E.

Having now the latitudes and longitudes of D and E, we can calculate the latitudes of various points on the great circle arcs FD and ET in the manner explained in § 35.

If we remember that the latitude of the limiting parallel is the latitude of the vertex for each great circle arc, we may very easily find the longitudes of D and E by Towson's tables. In the example above, entering the table with the latitude of the vertex 42° and latitude of F 29° 53′, we find the longitude from the vertex is 50° 20′; and with the latitude of T 34° 48′, we find the longitude from the vertex is 39° 28′.

CHAPTER VI.

THE DEAD RECKONING AND ESTIMATED POSITIONS.

---

38. The dead-reckoning position. — To find the position of the ship at any time when no observations for obtaining it are available, we have to utilise all the information that is at our disposal. The position of the ship depends primarily on the course steered and the distance run through the water, both of which should be known almost exactly, the first from the compass and the second from patent logs or other speed recorders, and from the revolutions of the engines. The position obtained from these data is called the dead-reckoning position, and is generally written D.R.

The information relating to the above data is tabulated at intervals by the Officer of the Watch in the ship's log. The Officer of the Watch should be careful when making these entries that the course should be the average one which he considers the helmsman has been actually steering the ship on as indicated by the standard compass, to which frequent reference should have been made. As regards the distance run on each course, he should take into consideration the reading of patent log or speed recorder, the known revolutions of the engines, the condition of the ship's bottom, and the state of the wind and sea.

39. The estimated position.—The position of the ship depends secondarily on the direction and distance she has been moved by currents, tidal streams, wind and sea, and imperfections in steering.

The wind and sea combined have the effect of causing leeway, that is, of driving a ship to leeward of her course. Leeway is defined as being the angle between a ship's fore-and-aft line and her wake.

In slow-moving sailing vessels this angle is allowed for as a correction to the course steered. In steamers, owing to the difficulty or impossibility of measuring this angle, the amount a ship has been set to right or left of her course is usually estimated and allowed for.

Another point to be considered when coasting is the possibility of an indraught into a deep bay or indentation of the coast.

The methods of estimating the currents and tidal streams are fully dealt with in Part III., and the effects of wind and bad steering can only be estimated by experience.

The position found, after taking all the above into consideration, is the most probable position of the ship that can be ascertained from the data available, and is called the estimated position.

When estimating the position of the ship, the greatest care should be taken that the fullest consideration is given to every factor which may influence her position, and it should not be concluded that the estimated position is the actual position, although, when all available data have been allowed for, it may be considered the most probable position.

When shaping course from an estimated position to approach land or dangers, THE GREATEST CAUTION IS NECESSARY AND SOUNDINGS SHOULD CONSTANTLY BE TAKEN WITH THE SOUNDING MACHINE; at the same time every endeavour should be made to check the estimated position of the ship by observations at the earliest opportunity.

It is obvious that after a short run of two to three hours the estimated position is not so likely to be in error as after a run of 24 hours; therefore, the longer the interval since the position of the ship was last fixed by observation, the greater the distrust with which we should view the estimated position, particularly in localities where the currents are strong and variable.

The dead reckoning and estimated positions can be obtained either by plotting on the chart or mooring board, or by calculation by aid of the traverse table; this table is so called because it was originally constructed to assist in finding the position of the ship after she had steered a number of different courses, when she was said to have made a "traverse."

It is impossible to lay down any law as to when either method of working the reckoning—that is, of finding the estimated position, from all the above data—should be used; but as a general rule, it will be found that the most convenient method under any particular circumstances is the correct one to use. We must bear in mind, however, the degree of accuracy required, and therefore the position should not be obtained by plotting on a chart on a small scale, because small errors in plotting would produce large errors in the position. When a chart on a large scale is not available, the position must be found by calculation. With reference to the term "reckoning," it may here be remarked that a ship is said to be ahead of her reckoning when the actual position is found to be in advance of the estimated position, and astern of her reckoning when the actual position is found to be behind the estimated position.

40. Working the reckoning by chart.—As an example of working the reckoning by chart, let us take the following:—

The position of the ship at 6^h A.M. was Lat. 49° 00′ N., Long. 7° 30′ W., and she steamed as shown in the following extract from the ship's log. During the whole time the current was estimated to be setting E.S.E. (Mag.) 1 knot. The effects of tidal streams, wind, and sea were estimated to be nil.

Hours.	Patent Log.	Distance Run.		Standard Compass Courses.	Deviation of Standard Compass.	Revolutions per Minute.	Remarks.
		Miles.	Tenths				
7	175·0	15	0	S. 40° E.	4° E.	90·2	7.20 altered course to N. 60° E. P. Log 180·0.
8	190·0	5 10	0 0	,, N. 60° E.	,, 1½° E.	89·9	8.15 altered course to N. 80° W. P. Log. 193·7.
9	205·0	3 11	7 3	,, N. 80° W.	,, 4° W.	90·1	9.0 altered course to N. 25° E.
10	220·0	10 5	0 0	N. 25° E. N. 30° W.	2° W. 4° W.	90·0	9.40 altered course to N. 30° W. P. Log. 215·0.
11	232·0	6 6	0 0	,, N. 68° E.	,, 2° E.	61·0	10.0 reduced to 12 knots.
12	244·0	12	0	,,	,,	60·0	10.30 altered course to N. 68° E. P. Log. 226·0.

It will be noticed from the above that from 6^h A.M. to 7^h 20^m A.M. the ship steamed S. 40° E. by compass, 20 miles. From a reference to the variation chart it has been found that the compass engraved on the chart in use (Fig. 32), for variation 18° 16′ W., is correct.

We have to lay off a course and distance S. 40° E. by standard compass, 20 miles, from the position on the chart marked 6^h A.M.

Compass course - -	S. 40° E.
Deviation - -	4 E.
Magnetic course -	S. 36 E.

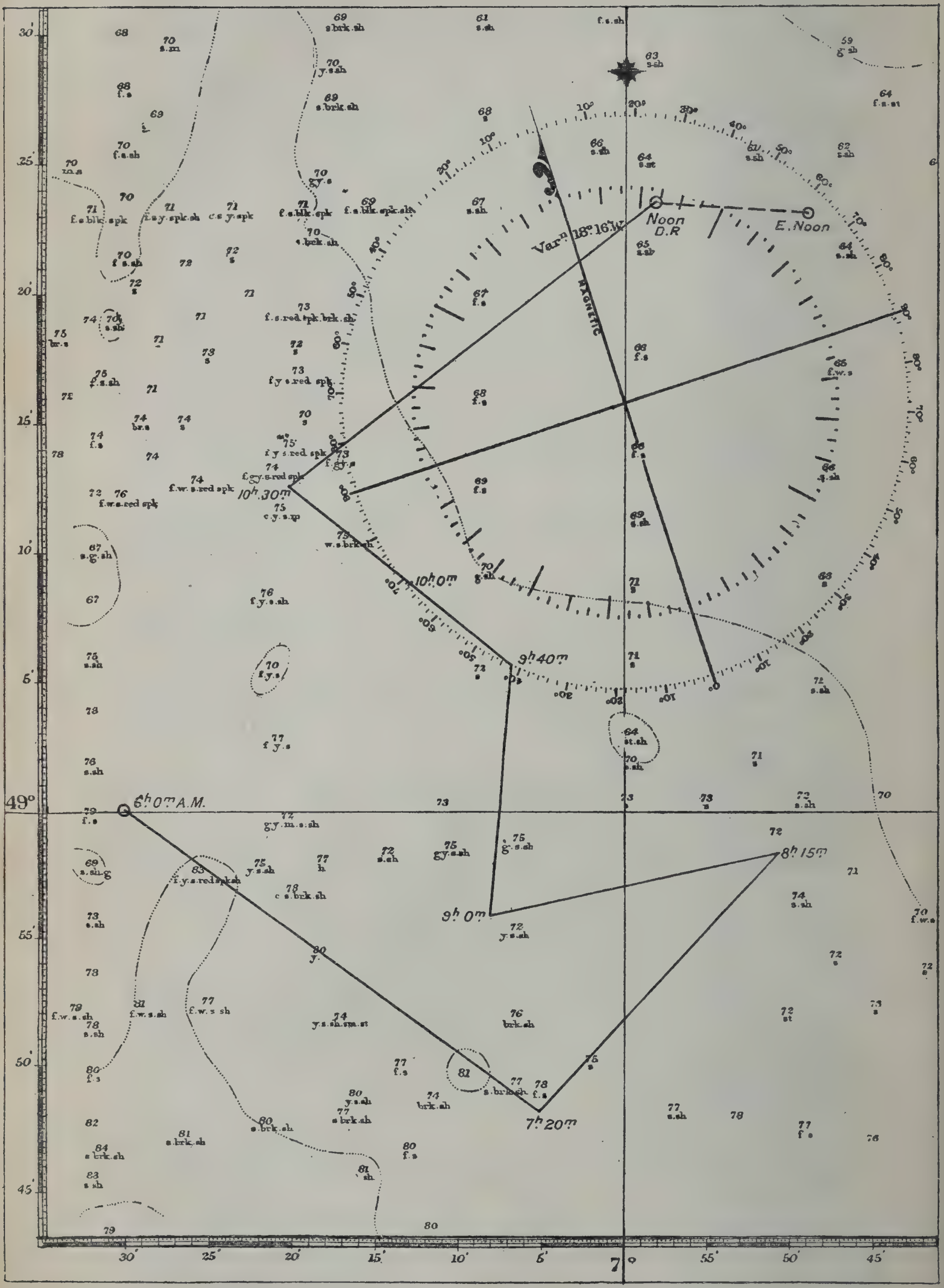

6h 0m A.M.
7h 20m
8h 15m
9h 0m
9h 40m
10h 0m
10h 30m
Noon D.R
E. Noon
Varn 18°16'W
Magnetic
49°
7°
30'
25'
20'
15'
10'
5'
55'
50'
45'

Fig. 32.

Place the parallel rulers on the engraved compass so that an edge lies on the graduations of S. 36° E. and N. 36° W. and on the centre of the compass. Transfer the ruler till its edge lies on the 6^h A.M. position, and from this position draw a line in the direction S. 36° E. (magnetic). From the scale of latitude on the chart, take with the dividers a length of 20′ of latitude from that part of the scale which is in approximately the same latitude as the ship, and measure this distance from the 6^h A.M. position along the line already drawn. The position thus obtained is the D.R. position at $7^h\ 20^m$ A.M.

At $7^h\ 20^m$ A.M. the course was altered to N. 60° E. by compass, and this course was maintained till $8^h\ 15^m$ A.M., so that the distance run on this course was 13·7 miles.

Compass course	-	N. 60° E.
Deviation -	-	$1\frac{1}{2}$ E.
Magnetic course	-	N. $61\frac{1}{2}$ E.

Lay off this course and distance as above, and the position obtained will be the D.R. position at $8^h\ 15^m$ A.M.

In a similar manner the other courses steered and distances run may be laid off, and the D.R. position of the ship obtained at any moment by reference to the scales of latitude and longitude on the chart. From the chart, Fig. 32, we observe that the D.R. position at Noon is Lat. 49° $23\frac{3}{4}'$ N., Long. 6° $58\frac{1}{4}'$ W.

To obtain the estimated position of the ship at Noon, the available data are—current E.S.E., 6 miles; tidal stream, nil; wind and sea, nil. The estimated position is therefore found by laying off a course and distance E.S.E. 6 miles from the D.R. position. We find that the estimated position at Noon is Lat. 49° $23\frac{1}{4}'$ N., Long. 6° 49′ W.

41. Working the reckoning by calculation.—We will now show with the same example how the D.R. and estimated positions may be found by calculation.

Firstly, it is necessary to correct all courses for deviation and variation, as the traverse table should be entered with true courses; then, by reference to the traverse table we find how much difference of latitude and departure the ship has made on each course. The total difference of latitude made is the algebraical sum of the various *d* Lats. The total departure made is assumed to be the algebraical sum of the departures made on the various courses. Where the distances run on the various courses are great, or the latitude high, or both, the error due to this assumption is considerable, but for a traverse which covers only a few hours' steaming no appreciable error is introduced.

The total *d* Lat. applied to the latitude of the last observed position gives the D.R. latitude required. With the total departure and the middle latitude (between the D.R. latitude and the latitude of the last position, we can, by aid of the table in Inman's for converting departure into *d* Lat., or by the traverse table, find the *d* Long. made from the last position; this *d* Long. applied to the longitude of the last position gives the D.R. longitude required. The working of the example is shown below:—

Compass Course.	Deviation.	Magnetic Course.	Variation.	True Course.	Distance.	*d* Lat.		Dep.	
						N.	S.	E.	W.
S. 40° E.	4° E.	S. 36° E.	18¼° W.	S. 54¼° E.	20·0	—	11·7	16·2	—
N. 60 E.	1½ E.	N. 61½ E.	,,	N. 43¼ E.	13·7	10·0	—	9·4	—
N. 80 W.	4 W.	N. 84 W.	,,	S. 77¾ W.	11·3	—	2·4	—	11·0
N. 25 E.	2 W.	N. 23 E.	,,	N. 4¾ E.	10·0	10·0	—	0·9	—
N. 30 W.	4 W.	N. 34 W.	,,	N. 52¼ W.	11·0	6·8	—	—	8·7
N. 68 E.	2 E.	N. 70 E.	,,	N. 51¾ E.	18·0	11·3	—	14·0	—
						38·1	14·1	40·5	19·7
						14·1		19·7	
					Total *d* Lat.	24.0N	Total Dep.	20·8E.	

Latitude at 6h A.M. - 49° 00′ N.
d Lat. - 24 N.

D.R. Lat. Noon - 49 24 N.
Latitude at 6h A.M. - 49 00

2/98 24

Middle latitude - 49 12

With departure 20′·8 and middle latitude 49° 12′, we find from the table in Inman's that the *d* Long is 32′.

Longitude at 6h A.M. - 7° 30′ W.
d Long. - - 32 E.

D.R. Long. Noon - 6 58 W.

D.R. position at Noon, Lat. 49° 24′ N., Long. 6° 58′ W.

To find the estimated position at noon we must take account of the current in the interval, and consider another course, E.S.E., 6 miles; this is equivalent to S. $85\frac{3}{4}°$ E. (true), 6 miles since the current is always given as magnetic. The *d* Lat. and departure for this are 0′·4 S. and 6′·0 E.

D.R. Lat. Noon.	49° 24′ N.		D.R. Long. Noon,	6° 58′ W.
d Lat. -	0·4 S.,	Dep. 6′·0 E.,	*d* Long. -	9 E.
Estimated latitude, noon.	49 23·6 N.		Estimated longitude, noon.	6 49 W.

42. Current by difference between dead-reckoning and observed positions.—If the position of the ship is found by observation to differ from the estimated position, it is obvious that some of our data are incorrect. As it is impossible to determine which of the data has been wrongly estimated, the difference between the actual and the D.R. positions is attributed to the current alone, because this generally has the greatest effect in displacing the ship. For example, in the preceding article suppose that the actual position of the ship at noon was found to be Lat. 49° 27′ N., Long. 6° 46′ W. The difference between the D.R. position and this position is expressed by finding the course and distance from the former to the latter, and assuming that this course and distance were due to the set and drift of the current in the interval.

D.R. position, noon	Lat. 49° 24′ N.,	Long. 6° 58′ W.
Observed position, noon	Lat. 49 27 N.,	Long. 6 46 W.
	d Lat. 3 N.,	*d* Long. 12 E.

With middle latitude $49°\frac{1}{2}$ N., and *d* Long. 12′ E., we find the departure to be 7′·8 E. With *d* Lat. 3′ N., and departure 7′·8 E., we find the course and distance to be N. 69° E., 8·4 miles, which gives the set and drift of the current as N. 69° E. (true) 1·4 knots.

43. Keeping the reckoning in a tideway.—The direction and rate of a tidal stream varies at different places and at different times of the day, so that, when a ship steers through a tideway, it is necessary to find the estimated position at frequent intervals. It is convenient to plot the estimated position hourly and on every change of course. An example of plotting the estimated position for a ship steering through a tideway for five hours is shown on the chart, Fig. 33.

At 5^h A.M. the ship's position was Lat. 50° 10′ N., Long. 4° 10′ W., and from this position she shaped course S.W. (magnetic), at a speed of 7·8 knots.

From 5^h A.M. to 6^h A.M. it is found from the tidal atlas that the tidal stream had probably set the ship N. by E. 1′. From the 5^h A.M. position lay off a line *FA*, S. 45° W., 7·8 miles. The

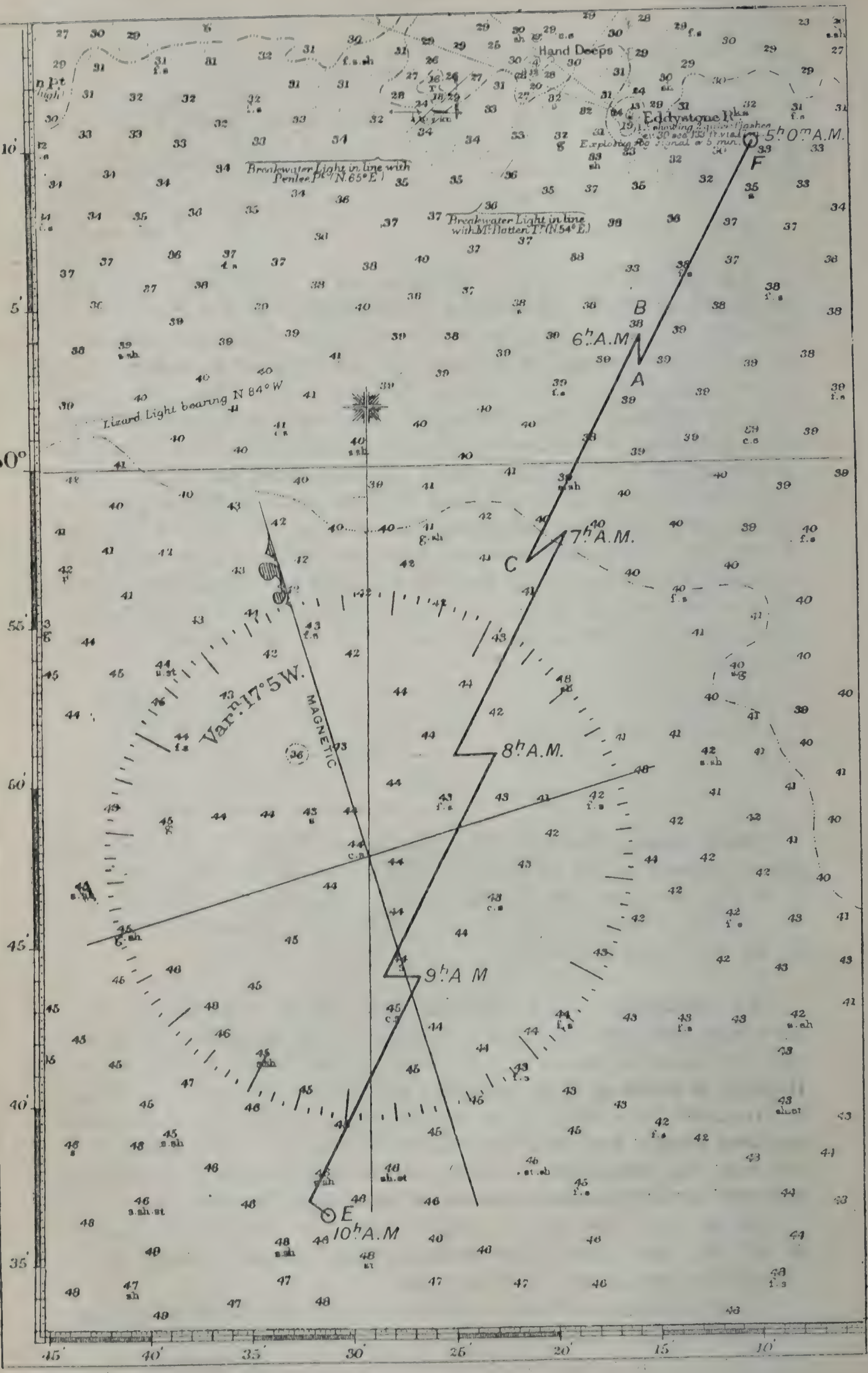

Hand Deeps
Eddystone Ltho
Exploding Fog Signal ev 5 min.
5h 0m A.M.
F
Breakwater Light in line with Penlee Pt. (N.65°E.)
Breakwater Light in line with Mt. Batten T. (N.54°E.)
B
6h A.M.
A
Lizard Light bearing N 84° W
C
7h A.M.
Varn. 17°5 W.
MAGNETIC
8h A.M.
9h A M
E
10h A.M
10'
5'
50°
55'
50'
45'
40'
35'
45'
40'
35'
30'
25'
20'
15'
10'

Fig. 33.

D.R. position at 6^h^ A.M. is at *A*. From *A* lay off a line *AB*, N. by E., 1 mile, to allow for the tidal stream experienced between 5^h^ A.M. and 6^h^ A.M. The estimated position of the ship at 6^h^ A.M is at *B*. From *B* lay off *BC*, S. 45° W., 7·8 miles, and note that the direction and rate of the tidal stream between 6^h^ A.M. and 7^h^ A.M. has been E.N.E., 1½ knots. Lay this off as before, and obtain the estimated position at 7^h^ A.M. Proceeding in a similar manner we find the estimated position at the end of every hour as shown on the chart.

44. Track of a ship while turning.—When a ship alters course, she does not turn instantaneously about a point on to the new course, but describes a curve from the time when the helm is put over to the time when she is steadied on the new course, as shown in Fig. 34. *AX* is the original track of the ship, *X* is the point where the helm is put over, *B* the point where the ship arrives on her new course, having described the curve *XDB* in the interval. In order to lay off the new course of the ship, we must know the position of *B* relative to *X*—in other words, we must know the length of *XB* and the angle *EXB*. Now from the turning trials of the ship, which are carried out with various angles of helm, her track while turning with any particular angle of helm may be plotted; and the angle *EXB* and the length *XB*, which correspond to any particular alteration of course, may be measured.

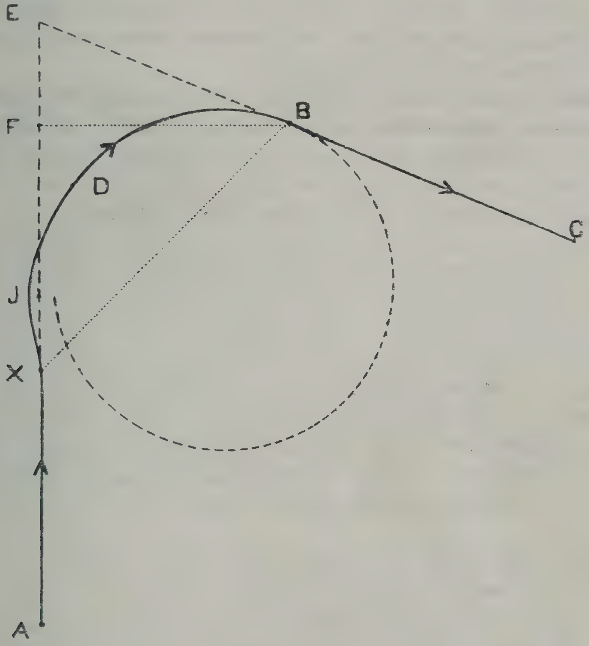


FIG. 34.

Now as the direction of *AX* is known, the direction of *XB* may be found; the direction and length of *XB* are called the intermediate course and distance. If, therefore, the position where the helm is put over be known, it is possible by means of the intermediate course and distance, to lay down the point *B* from which to lay off the new course.

Another method of laying off the new course is to lay it off from the point *E*, which is the intersection of the new and original tracks; the distance *XE* is called the "distance to new course," and is tabulated for every ship for alterations of course up to 12 points; for larger alterations, this method should not be used, because the distance *XE* becomes inconveniently great, being infinite for an alteration of course of 16 points.

The track of a ship while turning is different for different angles of helm, and for a particular angle of helm, on a calm day and in smooth water, is approximately constant; wind and sea are liable to cause a ship to deviate considerably from her normal path. No rules can be laid down as to the effects of wind and sea on the path of a ship while turning, and they can only be allowed for after experience.

In cases where the available manœuvring space is very restricted it is desirable, before entering such a harbour or channel, to plot the approximate track of the ship, while turning, on the chart, and this may be easily done by means of the advance and transfer. The advance is the distance the centre of gravity of the ship has advanced in the direction of her original course, measured from the point where the helm was put over—(the distance *XF* for the alteration of course shown in Fig. 34). The transfer is the distance the centre of gravity of the ship has been transferred in the direction at right angles to her original course—(*FB* for the alteration of course shown). The transfer for an alteration of course of 16 points is called the tactical diameter of the ship for the particular angle of helm which has been used. The advance and transfer for various alterations of course and angles of helm should be tabulated for every ship.

To plot the approximate track, with half the tactical diameter as radius, describe a circle to touch the original track at *J*, Fig. 34, *XJ* being the advance for a 16 point turn.

While a ship is turning through the first 16 points, her speed does not remain uniform, but becomes very much reduced; consequently, when steadied on her new course, some little time will elapse before the original speed is regained, and therefore, unless a patent log, which indicates the distance run through the water, is available, the mean speed of the ship to the time when the next alteration of course takes place has to be estimated. The percentage of the loss of speed during any alteration of course, and the times taken to complete various alterations of course at different speeds should be tabulated for every ship.

45. Keeping the reckoning during manœuvres.—When at fleet manœuvres, the alterations of course are frequently so numerous, and the distance run on each course is so short, that the curves described by the ship while making the various turns form a large proportion of the traverse; these curves must therefore receive more consideration than is usually necessary for the ordinary methods of keeping the reckoning.

On account of the possibility that at any moment it may be necessary for a ship engaged in manœuvres to shape a course for a particular position, it is essential that the reckoning should be kept in such a manner, that the position of the ship at any moment may be plotted on the chart with the least possible delay. The method of keeping the reckoning consists in considering that a ship starts from a known position *A*, Fig. 34, runs a course and distance *AX*, then turns about a point *X* and runs the intermediate course and distance *XB*, and again turns about the point *B* and runs the course and distance *BC*, &c.

In order to obtain the distance run on each course, it is convenient for an electric receiver from the patent log to be placed in the vicinity of the standard compass. If the reading of the patent log be taken at the point *A*, which is plotted on the chart, and again when the helm is put over for the alteration of course at *X*, the distance run in the direction *AX* is known. The intermediate distance *XB* is also known, but while the ship is passing from *X* to *B* she travels on the curved path *XDB*, and the distance run, as indicated by the patent log, will be greater than the intermediate distance. It is impossible to tell the instant when the ship arrives at *B*, and in order that the reading of the patent log may be noted at that instant, the length of the curved arc *XDB* is measured off from the plotted results of the turning trials, and is tabulated for various alterations of course. This length of the curved arc is the distance through the water that the ship actually steams between the points *X* and *B*, and, if added to the reading of the patent log at *X* gives the reading of the patent log at *B*. This length of the curved arc is called the "Log correction" (Log Cor.).

In case of there being no patent log available, the distance run on each course must be calculated from the interval of time during which the ship was steering that course and from the estimated speed of the ship through the water. For the same reason as we required the Log correction we now require a time correction, which, if added to the time shown by a watch when the helm was put over, will give the time of arrival at *B*. This time correction may be found from the known length of the arc and the mean speed of the ship on that arc, and may be tabulated for various alterations of course and for various speeds.

A time correction should not be used when the alteration of course is greater than 16 points, because the wind and sea have a considerable effect on the time occupied by the ship in turning through very large angles. In such a case the time when the ship is steady on the new course should be noted and assumed to be the time at *B*.

For alterations of course which are not greater than 30°, it may be assumed without appreciable error that the intermediate course is coincident with the original course. Therefore, for such alterations of course, the distance run on the original course is the difference between the readings of the patent log at *A* and *B*. Similarly, if there is no patent log available, the distance run on the original course is that found by the method described above with the addition of the intermediate distance.

If a gyro-compass, which indicates true directions, is used, the reckoning may be calculated as explained in § 41. If a magnetic compass is used, the following procedure is adopted. The distance on any magnetic course may be resolved into its components in, and at right angles to, the magnetic meridian. As the traverse table is simply the solution of a large number of right-angled plane triangles, it may be used for resolving the distance on any magnetic course in these directions. For example, a distance of 2·84 miles on a magnetic course N. 35° W. may be resolved into its components

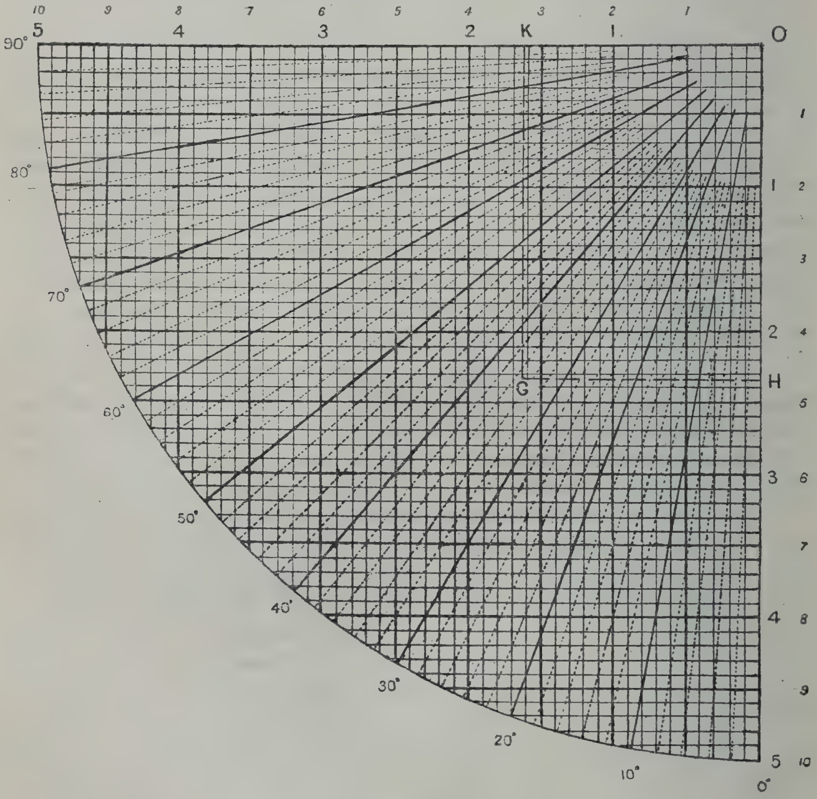


Fig. 35.

2·33 miles in the direction North (Mag.).
1·63 ,, ,, ,, West (Mag.)

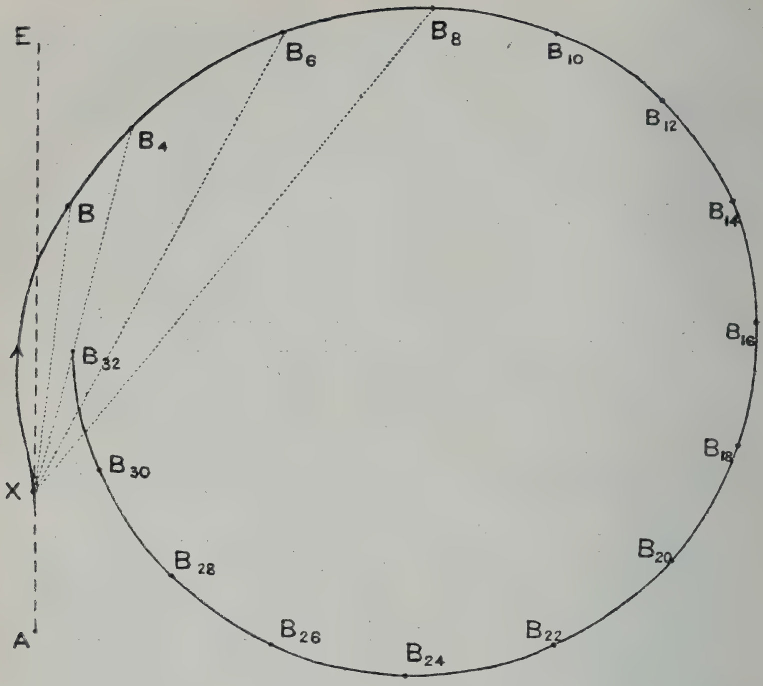
which, as may be seen from § 30, are the numbers given in the columns of the traverse table headed Diff. Lat. and Dep. respectively. In order to avoid the necessity for using a book, it is convenient to have a diagram, called a traverse diagram, as shown in Fig. 35, which may be pasted on a board. To use the diagram in the example given above, with a pair of dividers take off, from the right or top of the diagram, a distance equal to 2·84 miles on any convenient scale; with one leg of the dividers at the centre of the graduated arc O mark with the other leg a point G on the radiating line marked 35°. Measure the vertical distance GK, which will be found to be 2·33 miles, and mark it N. because the course is named North, and measure the horizontal distance GH, which will be found to be 1·63 miles, and mark it W. because the course is named West.

If the components of every distance in the North or South and East or West magnetic directions are tabulated in four columns headed N., S., E., and W., the sum of each column will give the distance the ship has moved in that particular direction. If the difference of the totals of the columns marked N. and S. be taken and marked with the name of the greater, the number of miles the ship has moved in the direction Magnetic North (or South) is known. Similarly, if the difference between the totals of the columns marked E. and W. be taken and marked with the name of the greater, the number of miles the ship has moved in the direction Magnetic East (or West) is known. The magnetic course and distance run in the whole interval may now be taken from the traverse diagram, by marking the point G on it such that GK is the difference between the columns marked N. and S., and GH the difference between the columns marked E. and W. The graduation where OG cuts the arc will be the magnetic course and will be named N. or S. and E. or W., according to the quadrant in which the ship has moved. The length of OG gives the distance run.

Whenever the course is altered, it is necessary to find the intermediate course to the position where the ship is steady on her new course; to do this it is necessary to apply the tabulated angle EXB, Fig. 34, to the last course. To save time, diagrams may be constructed which show readily the intermediate course without the necessity for calculation.

In order to explain the construction of these diagrams it will be convenient to construct them for the ship, whose turning circle is shown in Fig. 36.

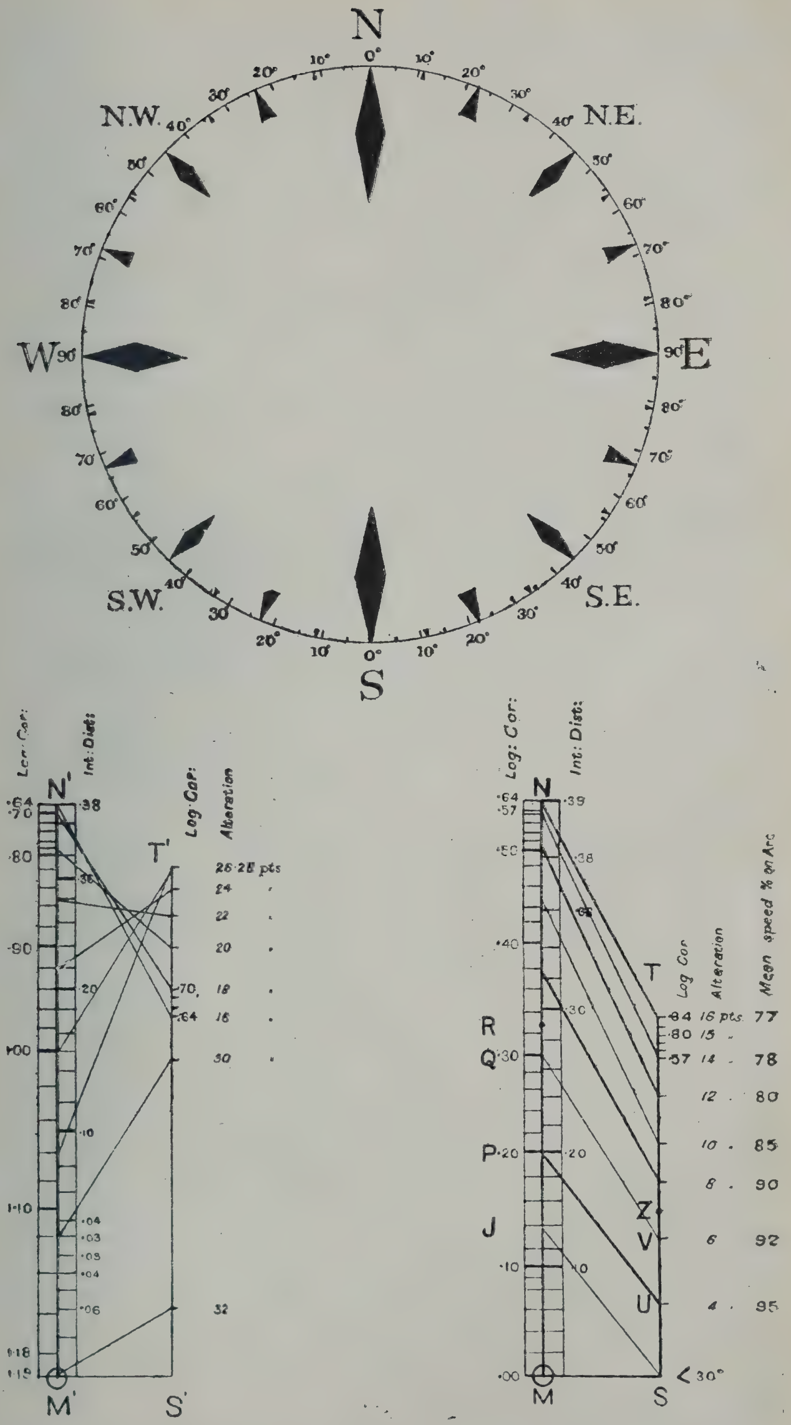
In Fig. 36, let B, B_4, B_6, B_8, &c., be the positions of the ship when she has turned through 30°, 4 points, 6 points, 8 points, &c., respectively, from her original course XE, and let X be the position where the helm was put over. The various measurements are made and the results are tabulated below.



Tactical diameter 750 yards.
Scale 200 yards = 1 inch.

FIG. 36.

Alteration of course.	Angle *EXB*.	Length of *XB*. Intermediate distance.	Length of Arc *XDB* Log correction.	Mean Speed per cent. on arc *XDB*.	Speed per cent. remaining at *B*.
	Degrees.	Miles.	Miles.		
30°	0	·14	·14	100	100
Points					
4	14	·20	·20	95	90
6	28	·27	·30	92	82
8	39	·33	·38	90	75
10	48	·37	·45	85	74
12	57	·38	·51	80	73
14	67	·39	·57	78	72
16	76	·38	·64	77	70
18	85	·37	·71	—	70
20	96	·33	·78	—	70
22	106	·28	·85	—	70
24	117	.22	·92	—	70
26	124	·15	1·00	—	70
28	124	·09	1·06	—	70
30	67	·03	1·12	—	70
32	14	·08	1·19	—	70



Alteration greater than 16 points.

Alteration less than 16 points

Fig. 37.

The upper diagram of Fig. 37, called the compass diagram, represents a compass card, and forms a scale for the construction and use of the lower diagrams. We will first construct the lower diagram marked "Alteration less than 16 points." Draw two parallel lines, *MN* and *ST*, at any convenient distance apart, and at right angles to a base line *MS*. From the compass diagram, measure off the chord for 4 points with a pair of dividers, and lay off this distance *MP* on the left hand line. Along *ST* lay off *SU* the chord for 14° which is the value of the angle *EXB*, corresponding to an alteration of course of 4 points; join *PU*. Similarly, lay off *MQ* the chord for 6 points and *SV* the chord for 28° and join *QV* and so on. Lay off *MJ* the chord for 30° and join *JS*.

Tabulate the log correction, the intermediate distance and other data, as shown in the diagram.

The diagram for alterations greater than 16 points is constructed in a similar manner. It will be seen that the chords for alterations of course of more than 16 points become successively less, whilst at first the chords for the angle *EXB* become successively greater, so that the lines joining corresponding points in some cases cross one another.

To use the diagrams for finding the intermediate course and distance and log correction, corresponding to any alteration of course, let us take the following:—

Example.—A ship is steering S. 60° W. (Mag.) and the helm is put over for an alteration of course to starboard to N.W. The reading of the patent log when the helm was put over was noted to be 37·2.

It is required to find the intermediate course (magnetic) and distance and the log correction.

Place the legs of the dividers on the graduations of the compass diagram corresponding to the old and new magnetic courses, then the distance spanned by the dividers is the chord for the alteration of course. On the diagram for alterations less than 16 points lay off this chord *MR*, and note that against the point of the dividers at *R* are tabulated Log Cor. ·33 miles and Int. Dist. ·29 miles. The eye being guided by the transverse lines, note that the corresponding point to *R* on the line *ST* is *Z*. Place one leg of the dividers at *S* and the other at *Z*, then the distance spanned by the dividers is the chord for the angle *EXB* corresponding to the given alteration of course. Place one leg of the dividers on the graduation S. 60° W. (the original course) on the compass diagram, and with the other sweep an arc to intersect the circumference of the compass diagram on the side to which the course was altered, in this case on the right as the alteration was to starboard, and note that the graduation at which it intersects is N. 86° W. which is the intermediate course required.

In the case of alterations greater than 16 points, the transverse lines cross one another and it appears to be difficult to determine the point in the line *ST*, but if care be taken to note between which transverse lines the point *R* is situated and if these lines are followed to the line *ST*, the point may be easily determined.

In the case of turns which are not greater than 30°, it is only necessary to note the intermediate distance tabulated against the point *R*, for, as explained above, in such a case, the intermediate course is practically the same as the original course.

46. Examples of keeping the reckoning during manœuvres.—The method to be adopted depends on whether a patent log (or other distance recording instrument) is available, or the distances have to be calculated from the time and speed. It is preferable to use a patent log, because it is extremely difficult to make allowance for the loss of speed occasioned by the helm being put over.

A reliable assistant should always, when possible, be employed to keep the reckoning, in order that this very important matter may have the undivided attention of one individual. The reckoning should be as carefully kept when manœuvring in sight of land as when in the open ocean. Only by constant practice in sight of land, where the results can be checked by observation, is it possible to be certain that the reckoning is kept in such a methodical manner, that the resulting position of the ship is free from all errors, other than those due to wrong estimation of the effects of tidal streams, currents, &c.

It should be understood that the various entries tabulated in the following examples would, in practice, be written down in the note book as each incident occurs. It is advisable to add up the four columns marked N., S., E. and W. as each page of the note book is completed, and to transfer the totals to the head of the next page in order to simplify the addition when the position of the ship is required.

Example.—Patent log available.

The ship, for which the diagrams in Fig. 37 have been constructed, was steering North (Mag.), and at 9^h A.M. her position was plotted on the chart and the reading of the patent log was noted to be 17·5. Subsequently, various alterations of course were made; the reading of the patent log and the time to the nearest minute were noted on each occasion of putting the helm over, and the letters *R* or *L* were noted in the margin of the note book against each entry, according as to whether the turn was made to right or left (to starboard or port).

At 10^h 36^m A.M. the magnetic course and distance run since 9^h A.M. were required in order to plot the position of the ship on the chart.

In order to render the working of the example clear, the intermediate courses and distances, log corrections and readings of the patent log depending on them are printed in italics;

the readings of the patent log, the difference between which is the distance run on each course, are bracketed together. The reckoning is kept as shown below.

—	Time.	P. Log.	Course.	Distance.	N.	S.	E.	W.
	h. m.							
	9 00	17·5	N.	4·40	4·40			
R	9 18	21·9	*N. 25° E.*	*·25*	·23		·11	
		·26						
		22·16	N. 60° E.	1·58	·79		1·37	
R	9 25	23·6						
		·14						
		23·74	E.	3·76			3·76	
R	9 41	27·5	*S. 32° E.*	*·38*		·32	·20	
		·51						
		28·01	S.W.	4·99		3·53		3·53
L	10 04	33·0	*S. 10° W.*	*·33*		·32		·06
		·38						
		33·38	S.E.	1·82		1·29	1·29	
R	10 14	35·2	*S. 48° W.*	*·34*		·23		·25
		·76						
		35·96	N.	4·44	4·44			
	10 36	40·4						
					9·86	5·69	6·73	3·84
					5·69		3·84	
					4·17 N.		2·89 E.	

From the traverse diagram, Fig. 35, with the above results 4′·17 N. and 2′·89 E. it is found that the course and distance run since 9ʰ A.M. is N. 35° E. (Mag.) 5·1 miles. This course and distance may now be drawn on the chart from the 9ʰ A.M. position, and thus the position of the ship at 10ʰ 33ᵐ A.M. is found.

The arrangement in which the entries should be written down, as shown in the above example, should be carefully studied, because only by following a regular procedure is it possible to be certain of avoiding mistakes. It will be seen that each course, whether a course actually steered or an intermediate course, is entered against the reading of the patent log when the ship commenced to steer that course, or was supposed to commence to steer that course, as the case may be; therefore, the distance run on each course steered is the difference between the readings of the patent log shown against that course and that shown against the next.

Should there be any error in the patent log, which, as will be explained in Part IV., is always stated as a percentage of the distance shown by the log, it must be applied to the resulting distance run in the whole interval as a percentage of that distance. For example, suppose that in the case considered above the error of the patent log was "underlogging 5 per cent." Then the resulting course and distance would be

$$\text{N. } 35^\circ \text{ E.(Mag.) } (5{\cdot}1 + \frac{5}{100} \times 5{\cdot}1) = \text{N. } 35^\circ \text{ E. (Mag.) } 5{\cdot}4 \text{ miles.}$$

The following is the working of the same example when no patent log is available; in this case the distance run on each course is calculated from the times and the estimated speed of the ship.

The nominal speed of the ship was 15 knots; the mean speed while steering any course has to be estimated, not only from the known percentage of the speed which remains when the ship is steadied on that course, but also from the interval of time during which the ship was steering that course; the distance run on any course cannot, therefore, be filled in until after the next alteration. It is convenient to note the estimated speed in brackets underneath each course as shown below. The time at which the helm was put over should be noted to the nearest tenth of a minute.

—	Time.	P. Log.	Course.	Distance.	N.	S.	E.	W.
	h. m.							
	9 00		N.	4·40	4·40			
			(15)					
R	9 17·6		*N. 25° E.*	*·25*	·23		·11	
	1·1	*·26*	*(13·9)*					
	9 18·7		N. 60° E.	1·44	·79		1·37	
			(13·25)	*·14*				
R	9 25·2							
	·5	*·14*	*(15)*	1·58				
	9 25·7		E.	3·76			3·76	
R	9 40·7		*S. 32° E.*	*·38*		·32	·20	
	2·5	*·51*	*(12)*					
	9 43·2		S.W.	4·99		3·53		3·53
			(14·5)					
L	10 03·8		*S. 10° W.*	*·33*		·32		·06
	1·7	*·38*	*(13·5)*					
	10·05·5		S.E.	1·82		1·29	1·29	
			(13·5)					
R	10 13·6		*S. 48°W.*	*·34*		·23		·25
	10 17·6		N.	4·44	4·44			
			(14·5)					
	10 36				9·86	5·69	6·73	3·84
					5·69		3·84	
					4·17N.		2·89E.	

In order to render the working of the example clear, the intermediate courses and distances, log and calculated time corrections and times depending on the latter are printed in italics; the two entries in the time column, the difference between which gives the interval during which the ship was steering each course, are joined by brackets.

As before, the total course and distance run between 9^h A.M. and 10^h 36^m A.M. is found to be N. 35° E. (Mag.) 5·1 miles.

If it is expected that a tidal stream or current exists, the magnetic direction and the distance, which it is supposed that the tidal stream or current will have moved the ship in the whole interval, may be tabulated and dealt with as another course and distance; the final position obtained will be the estimated position.

However much care may have been taken in keeping and working the reckoning, it must be borne in mind that the greatest caution must be exercised when it is necessary to make a landfall, or to shape a course to avoid a danger, from an estimated position so obtained. Even under the most favourable conditions, when the ship has been steaming on a steady course, and at a constant speed, it is sometimes found that the estimated position is many miles in error. Therefore, when there have been many alterations of course or speed, it is obvious that too much reliance should not be placed on the estimated position.

CHAPTER VII.

POSITION LINE BY OBSERVATION OF TERRESTRIAL OBJECTS.

47. Unreliability of the estimated position. Position line.—The estimated position of the ship, which has been discussed in the previous chapter, is so called because it is not necessarily the actual position, and for the following reasons. In the first place, the data for finding the dead reckoning position, namely compass course, variation, deviation, and distance run through the water, may all be more or less in error. However carefully the ship may have been steered, and however much care may have been taken in ascertaining the error of the compass and estimating the distance run through the water, yet these can only be obtained approximately; although the errors considered separately may be insignificant, they may so combine as to produce considerable error in the dead reckoning position derived from them.

In the second place, the estimated position depends, not only on the dead reckoning, but also on the degree of accuracy with which the tidal streams, currents, and the effects of wind and sea have been estimated.

As the tidal streams vary considerably both in strength and direction, and as in some parts of the world there are currents whose drifts vary between 10 and 50 miles per day, it is obvious that little reliance can be placed on an estimated position, even when the utmost care has been taken in making an estimate of the factors involved.

From this unreliability of the estimated position, we see the necessity for obtaining the position of the ship by other means, and this is done by reference to some object or objects whose position is accurately known. This reference must take the form of a measurement which can only be made, either by observing some angle, or by obtaining the distance of the ship from an object.

An observation of an angle or distance gives certain data from which we obtain a line (which may be drawn on the chart) somewhere on which the ship must lie to satisfy the data of the observation. This line is called a position line.

If two observations are taken, two position lines are obtained, and if these lines are drawn on the chart, the point where they intersect is the position of the ship.

There are various observations which may be taken with different navigational instruments to obtain the data to enable us to draw a position line on the chart, each of which will now be dealt with separately.

48. Position line by compass bearing.—If the bearing of an object is taken with the compass, and the compass error is applied, the true bearing of the object from the observer is obtained. Now there are an infinite number of positions from which the true bearing of the object is the true bearing thus obtained, and if all these points were joined, it would be found that they all lie on a curve.

In Fig. 38, let the true bearing of the object *A* be N. 60° W.

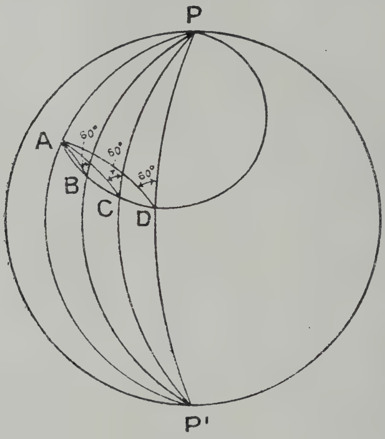


Fig. 38.

Let *ABCD* . . . . be the position line resulting from this observation: then, if the observer were at *D*, and *DA* were the arc of the great circle joining him to the object *A*, the angle *PDA* would be 60°; similarly, the angle *PCA* would be 60°, and so on for all points on the curve. If a point be selected close to *A*, it will be seen that the arc of the great circle joining the observer and the object is coincident with the curve, and therefore the position line makes an angle of 60° with the meridian of the object observed. For this reason, and owing to the very large radius of curvature of this curve (when represented on the Mercator's chart), which can never, at the object observed, be less than the radius of the earth, it is sufficiently accurate in practice to lay off the line *ABCD* . . . . on the chart as a straight line making an angle with the meridian equal to the true bearing; therefore the position line is drawn on a Mercator's chart as if it were a rhumb line, and is generally called a line of bearing.

The error in a position obtained by this approximation under the worst conditions is 1 mile when the distance is 63 miles and the latitude is 60°, and the error is less in lower latitudes, being less than ·4 mile for the same distance in latitude 30°.

In practice it is convenient to draw the line of bearing on the chart by means of the magnetic bearing of the object observed, the method being similar to that employed when laying off a magnetic course (§ 40).

As a large number of charts are now published on the gnomonic projection, it may be remarked that lines of bearing may be sufficiently correctly laid off on these charts by laying them off as straight lines, using the compass rose nearest to the estimated position of the ship. As these charts do not embrace a very large area, the errors involved are not great.

When correcting an observed compass bearing, that deviation should be used which corresponds to the direction of the *ship's head* at the time the bearing was taken, and it should be remembered that allowance should be made, when necessary, for the amount by which the variation as shown on the compass rose, is in error.

49. Position line by horizontal sextant angle.—If an angle is observed which is subtended by two objects *A* and *X*, the observer must lie somewhere on the circumference of a circle which contains this angle.

In Fig. 39, if the angle observed between the two objects *A* and *X* is 30°, the observer must lie somewhere on the segment of a circle at every point of which the line *AX* subtends an angle of 30°.

The segment of the circle *AOBX* is, therefore, the position line obtained from this observation.

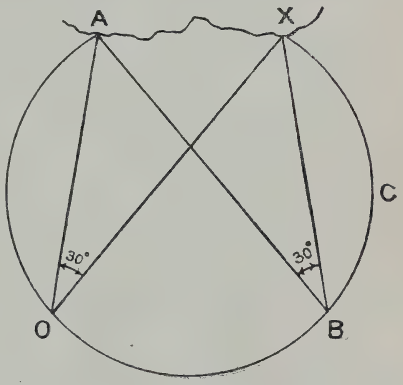


FIG. 39.

This position line may be represented on the Mercator's chart as a circle without appreciable error.

50. Position line by distance from an object.—If the distance of an object can be obtained, the ship must be situated on the circumference of a circle described with the object as centre and with the distance as radius. This circle is, therefore, the position line.

The distance from an object may be found in the following ways:—

(*a*) By rangefinder.

If the object is well defined, the rangefinder, provided it is in good adjustment, is by far the quickest and most accurate method of obtaining the distance, within the limits of the instrument.

(*b*) By sextant.

When the height of the object is known, the distance can be found by aid of the sextant. The sextant is an instrument for measuring angles and is described in Part IV.; angles measured with it have to be corrected for an instrumental error, called index error, which is denoted by I.E. Before explaining the method of finding the distance of an object by sextant angle, we have to explain what is meant by terrestrial refraction, altitude and depression, sea and shore horizons, dip of the sea horizon and dip of the shore horizon.

51. Terrestrial refraction.—Since the density of the atmosphere diminishes as its distance from the surface of the earth increases, a ray of light, passing from one point to another, does not travel in a straight line, but in a curve, which lies in a vertical plane containing the points, and is concave to the earth's centre; thus, in Fig. 40, an observer O sees the point X in the direction OT, because the ray of light from X travels along the curve XYO, and OT is the tangent to the curve at O. This apparent change in the direction of the terrestrial point X—namely the angle TOX—is called the terrestrial refraction of the ray XYO.

If the tangent at X to the ray of light intersects the tangent at O in T, the angles TOX and TXO are found to be approximately equal, and from a large number of experiments it has been found that the mean value of either of these angles is about $\frac{1}{13}$th of OCX.

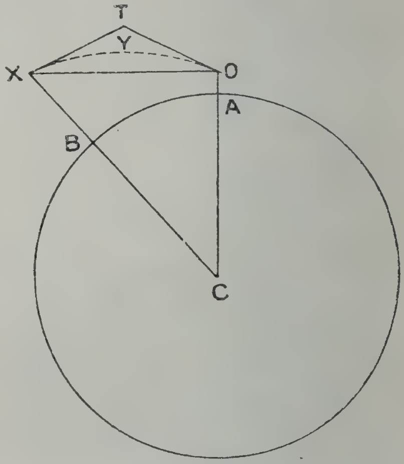


Fig. 40.

$$\text{Therefore, terrestrial refraction} = \frac{OCX}{13} \text{ approximately.}$$

Now the angle OCX, expressed in minutes of arc, is the number of nautical miles between A and B.

$$\text{Therefore, terrestrial refraction} = \frac{\text{distance}}{13}, \text{ approximately.}$$

52. Abnormal refraction.—The refraction is said to be abnormal when it differs from the value as found by dividing the distance by 13.

Refraction is likely to be abnormal when the temperatures of the water and air differ considerably, where currents of different temperatures meet, and where the sun is shining on large expanses of sandbanks or coral reefs. It is found to exist at times in a marked degree in the Red Sea, in the Persian Gulf, in the vicinity of the Gulf Stream, on the West Coast of Africa and in the Mediterranean.

53. Altitude of a terrestrial object.—When a point is above the horizontal plane through the observer's eye, its apparent altitude is the vertical angle between the apparent direction of the point and the horizontal plane passing through the observer's eye.

In Fig. 41, let *X* be the point, *OX* the ray of light from *X* to the observer's eye, and *OT* the tangent to the ray at *O*; then the apparent direction of the object is along the line *OT*, and the angle *TOH* is the apparent altitude of *X*.

Now the angle *TOX* is the refraction for the ray *OX*, and the angle *XOH*, which is the apparent altitude diminished by the refraction, is called the true altitude of the terrestrial point *X*.

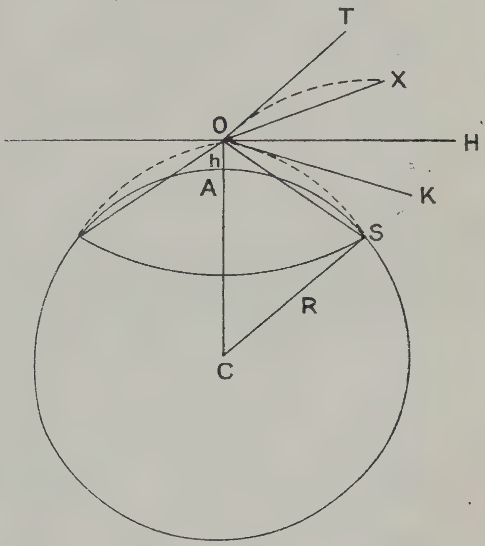


Fig. 41.

54. Depression of a terrestrial object.—When the point is below the horizontal plane passing through the observer's eye, as *S* in Fig. 41, the apparent depression of the point is the angle *HOK*, and the true depression is *HOS*.

55. The observer's sea and shore horizons. — The observer's sea horizon is the small circle of the earth where the sea and sky appear to meet.

The observer's shore horizon is the irregular line in which the sea and land intersect.

On board ship there is nothing to define the horizontal plane through the observer's eye, and it is impossible to directly measure an altitude or depression; consequently, the altitude has to be measured to the observer's sea or shore horizon, and this measurement is called the observed altitude. Therefore, if we know the apparent depression of the sea or shore horizon which is called the dip, the apparent altitude of a point is equal to its observed altitude diminished by the dip of the sea or shore horizon. Thus in Fig. 41, *OK* is the apparent direction of the sea horizon *S*, *HOK* is the dip, *OT* is the apparent direction of the point *X*, *TOK* is the observed altitude, *TOH* is the apparent altitude, and *XOH* is the true altitude of the point *X*.

56. Formula for the dip of the sea horizon.—In Fig. 42, let *O* be the observer's eye at a height *h* feet above sea-level, *SO* the curved ray by which the sea horizon is seen at *S*, *TO* and *TS* the tangents to the ray at *O* and *S*.

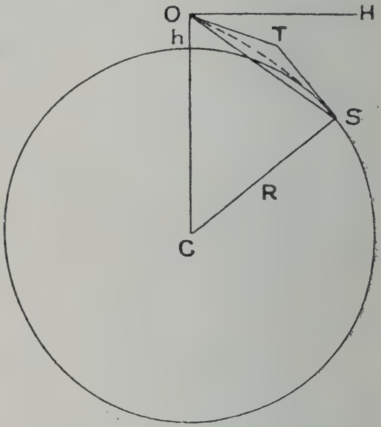


FIG. 42.

Let *OH* be the horizontal line passing through the observer's eye and in the same vertical plane as *S*.

The angle $TSO = TOS =$ the terrestrial refraction for the ray $OS = r$, say.

As the curved ray touches the earth at *S*, the tangent *TS* also touches it at *S*; therefore $OSC = 90° - r$.

Now

$$\begin{aligned} COS &= 180° - OCS - OSC. \\ &= 180° - OCS - 90° + r. \end{aligned}$$

Therefore, denoting the angle *OCS* by *C*,

$$COS = 90° + r - C.$$

$$\begin{aligned} \text{Again, } HOT &= 90° - COS - SOT \\ &= 90° - (90° + r - C) - r \\ &= C - 2r. \end{aligned}$$

Now *HOT* is the dip, and as $r = \dfrac{C}{13}$, we have

$$\text{Dip} = \frac{11}{13} C,$$

so that, in order to find the dip we must find *C*.

In the triangle *OCS* ,

$$\frac{\sin COS}{\sin CSO} = \frac{SC}{CO} = \frac{R}{R + h}$$

where *R* is the earth's radius in feet.

Now

$$\sin COS = \sin (90° + r - C) = \cos (C - r),$$

$$\text{and } \sin OSC = \sin (90° - r) = \cos r.$$

$$\therefore \frac{\cos (C - r)}{\cos r} = \frac{R}{R + h},$$

$$\therefore \cos C + \sin C \tan r = \frac{R}{R + h}.$$

Since *C* and *r* are small angles, we may put the trigonometrical ratios in terms of their circular measures, and we have

$$1 - \frac{C^2}{2} + Cr = \frac{R}{R + h}.$$

Substituting $\frac{C}{13}$ for r, we have

$$\frac{11C^2}{26} = \frac{h}{R+h}.$$

Neglecting h in the denominator on the right,

$$C = \sqrt{\frac{26h}{11R}}, \text{ nearly.}$$

Therefore, if C is expressed in minutes of arc,

$$C = \operatorname{cosec} 1' \sqrt{\frac{26\,h}{11\,R}} = \operatorname{cosec} 1' \sqrt{\frac{26\,h}{11 \times 20890550}} = 1\cdot15\sqrt{h}.$$

$$\text{Therefore dip} = \frac{11}{13} \times 1\cdot15\sqrt{h} = \cdot98\sqrt{h}.$$

The dip of the sea horizon, calculated from the formula above, is tabulated for various heights of eye in Inman's tables.

It will be seen that the accuracy of the tabulated dip depends on the refraction being $\frac{1}{13}$th of the distance, which is its mean value; so that, where there is abnormal refraction, the actual dip differs from that tabulated—in other words, the apparent altitude of a point is in error by the amount that the apparent position of the sea horizon is in error. A table, which may be taken as a guide as to what error to expect in calm weather with different temperatures of sea and air, is given on page x of Inman's tables, but it should be remembered that the refraction may not be the same in all directions, and, consequently, too much confidence must not be placed in the table.

It will be observed that the table gives maximum values for the correction for a height of eye of 60 feet; therefore, when abnormal refraction is known or suspected to exist, which may often be detected by an apparent unsteadiness of the sea horizon, it would appear that altitudes should be observed from a position the height of which should differ considerably from 60 feet.

57. Distance of the sea horizon.—In the preceding investigation it was found that the angle C expressed in minutes of arc is given by $C = 1\cdot15\sqrt{h}$; therefore the distance of the sea horizon for an observer whose eye is h feet above sea level is $1\cdot15\sqrt{h}$ nautical miles.

The distances of the sea horizon are tabulated for various heights of eye in Inman's tables.

When a powerful light, L, Fig. 43, of a lighthouse first becomes visible to an observer O over the horizon on a clear night, a close

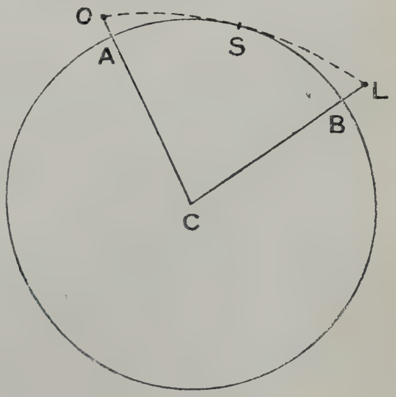


FIG. 43.

approximation to its distance may be made by making use of the table for the distance of the sea horizon, for the point *S* is the common sea horizon of *O* and *L*, and therefore the distance of the observer from the lighthouse is the sum of the distances of the sea horizon from *O* and from *L*.

The height of a light given on the chart is that above high water of spring tides, and as the height of the light used must be its actual height above the water at the time of observation, an allowance for the state of the tide should be made when necessary. For example, suppose an observer, whose height of eye is 50 feet, sees the Bass Rock Light (150 feet above high water) just showing over his sea horizon, the height of the tide at the time being 6 feet below the level of high water of spring tides. The height of the light above the sea-level is 156 feet.

From the table for the distance of the sea horizon in Inman's tables, 156 feet gives *BS* as 14·3 miles, and 50 feet gives *AS* as 8·1 miles; therefore the distance *AB* is 22·4 miles, from which it may be concluded that the distance of the lighthouse is about 22 miles.

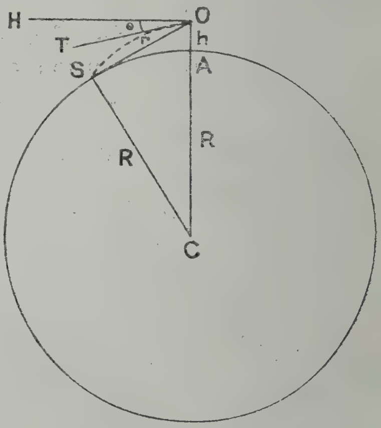


FIG. 44.

58. Formula for the dip of the shore horizon.—In Fig. 44 let *S* be a point of the shore horizon, and *O* the observer's eye at a height of *h* feet above sea-level.

Let *OT* be a tangent to the curved ray *OS*, then if *OH* is horizontal, the angle *HOT* is the dip of the shore horizon. Denote *HOT* by θ and the refraction *TOS* by r.

In the triangle *OSC*,

$$\frac{\sin CSO}{\sin COS} = \frac{R+h}{R}$$

where R is the earth's radius in feet.

Now

$$CSO = 180° - C - (90° - r - \theta) = 90° + r + \theta - C.$$

$$\therefore \frac{\cos(r+\theta-C)}{\cos(r+\theta)} = \frac{R+h}{R},$$

$$\therefore \cos C + \sin C \tan(r+\theta) = \frac{h}{R} + 1,$$

$$\therefore \sin C \tan(r+\theta) = \frac{h}{R} + 2\sin^2\frac{C}{2},$$

$$\therefore \tan(r+\theta) = \frac{h}{R\sin C} + \tan\frac{C}{2},$$

Therefore, since r, θ and C are all small angles

$$(r+\theta)' \sin 1' = \frac{h}{RC} + \frac{C'}{2}\sin 1'.$$

Let d be the distance in nautical miles between A and S, then

$$RC = 6080d. \quad \text{Also } r = \frac{C'}{13}.$$

Therefore
$$\theta = \frac{h}{6080\, d \sin 1'} + \frac{C'}{2} - \frac{C'}{13}.$$

Now the number of minutes in C is the same as the number of nautical miles in d.

∴ Dip of shore horizon in minutes of arc

$$= \cdot 5654 \frac{h}{d} + \frac{11}{26} d,$$

$$= \cdot 5654 \frac{h}{d} + \cdot 423\, d,$$

where h is in feet and d is in nautical miles.

The dip of the shore horizon is tabulated in Inman's tables for various distances and heights of eye.

59. Distance by vertical sextant angle.—

Case 1.—When the point observed is vertically over the shore horizon.

In Fig. 45, let BC be a vertical cliff of height H feet above the sea-level C. Let O be the observer's eye at a height h feet above the sea-level A. Let the angle subtended by BC at the observer's eye be α. Let a circle described about the triangle OBC cut AC in D and AO produced in E.

The horizontal distance of the observer from the foot of the cliff is AC.

Now

$$\begin{aligned} AC &= DC + AD \\ &= H \cot \alpha + \frac{AO.\, AE}{AC}, \\ &= H \cot \alpha + \frac{h\,(H - h)}{AC}, \end{aligned}$$

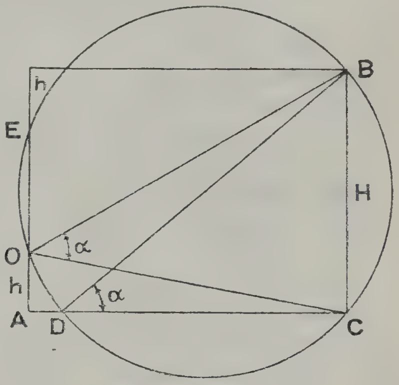


Fig. 45.

Now if AC is greater than H, that is, if the distance of the ship from the shore horizon is greater than the height of the cliff, the second term is less than h. Therefore, if we assume that the distance is $H \cot \alpha$, the error will be less than h provided that AC is greater than H.

In this and the following case, refraction and the curvature of the earth have been neglected; no appreciable error is caused thereby, because the distances involved are necessarily very small.

Case 2.—When the point observed is not vertically over the shore horizon.

In Fig. 46, let F be the shore horizon, and BOF the observed angle α. Let a circle described about the triangle OFB cut AC in D, AO produced in E, and CB produced in G.

Then

$$AC = DC + AD = H \cot \alpha + \frac{AO.AE}{AF} = H \cot \alpha + h\frac{CG + (H - h)}{AF}.$$

Now

$$CG = \frac{DC.FC}{H}.$$

Therefore

$$\begin{aligned} AC &= H \cot \alpha + h\left(\frac{H-h}{AF}\right) + h.\frac{DC.FC}{AF.H} \\ &= H \cot \alpha + h\left(\frac{H-h}{AF}\right) + h\frac{FC}{H}\left(\frac{AF - AD + FC}{AF}\right) \\ &= H \cot \alpha + h\left(\frac{H-h}{AF}\right) + h\frac{FC}{H}\left(1 - \frac{AD}{AF} + \frac{FC}{AF}\right). \end{aligned}$$

Now if $AF > H$, and $H > FC$, then $AF > FC$, and the second term on the right is less than h, while the third term is less than $2h$.

Therefore, if we take the distance as $H \cot \alpha$, the error will be less than $3h$ provided $AF > H > FC$; that is, if the distance of the shore horizon is greater than the height of the point observed, and the height of the point observed is greater than its horizontal distance from the shore horizon.

It will be seen that the error due to taking the distance as $H \cot \alpha$ places the ship nearer the object observed than is really the case.

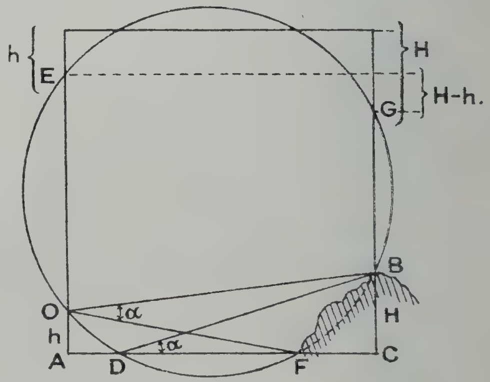


FIG. 46.

When the observed angle is less than 3° the following modification of the formula Distance = $H \cot \alpha$ may sometimes be found useful:—

$$\text{Distance} = H \cot \alpha = \frac{H}{\sin \alpha} \text{ nearly } = \frac{H}{\alpha'' \sin 1''}.$$

Therefore if H is expressed in feet, the distance is given in nautical miles by

$$\frac{H}{\alpha'' \, 6080 \sin 1''} = \frac{H \times 34}{\alpha''}$$

Therefore the distance in nautical miles $= \dfrac{\text{Height in feet} \times 34}{\text{Observed angle in seconds}}$.

Case 3.—When the base of the object observed is below the observer's sea horizon.

In Fig. 47 let B be the summit of a mountain, whose height DB is H feet above sea-level.

Let the observed altitude of B, as measured from the sea horizon, when diminished by the dip, be α. Then α is the apparent altitude of B (TOK in Fig.).

Suppose r to be the refraction for the ray OB, then the true altitude of B, viz., the angle BOK, is $\alpha - r$.

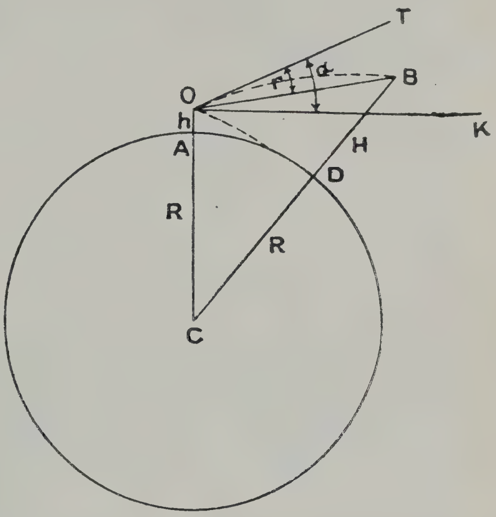


FIG. 47.

In the triangle OBC, the angle $COB = 90° + \alpha - r$, and the angle $CBO = 180° - C - (90° + \alpha - r) = 90° - C - \alpha + r$.

Now

$$\frac{\sin CBO}{\sin COB} = \frac{R+h}{R+H},$$

where R is the radius of the earth in feet.

$$\therefore \frac{\cos(C + \alpha - r)}{\cos(\alpha - r)} = \frac{R+h}{R+H}.$$

$$\text{Therefore } \cos(C + \alpha - r) = \frac{R+h}{R+H} \cos(\alpha - r).$$

Therefore if we can calculate the angle C from this formula and reduce it to minutes of arc, the number of minutes will be the number of nautical miles in the arc AD. It will, however, be seen that in the formula there are two unknowns, C and r, but as r is only $\frac{1}{13}$th of C, we may first find an approximate value of C by neglecting r altogether, and so find an approximate distance. With this approximate distance we may find the refraction r, and, by repeating the operation, a better value for the distance.

Now as the formula involves the radius of the earth expressed in feet, which is a very large number compared with H and h, it is necessary in making the calculation to obtain the logarithms of $R + H$ and $R + h$ very accurately. To avoid the necessity for so doing we shall put the formula in a form which does not involve the radius of the earth.

Taking logarithms (to the base 10) of each side of the equation, we have

$$\log\cos(C + a - r) = \log\cos(a - r) + \log\frac{1 + \frac{h}{R}}{1 + \frac{H}{R}}$$

$$= \log\cos(a - r) - \frac{\log_e\left(1 + \frac{H}{R}\right) - \log_e\left(1 + \frac{h}{R}\right)}{\log_e 10}$$

$$= \log\cos(a - r) - \frac{H - h}{R\log_e 10}, \text{ nearly.}$$

$$\text{Let } x = \frac{H - h}{R\log_e 10}$$

then

$$\begin{aligned} \log x &= \log(H - h) - \log(R\log_e 10) \\ &= \log(H - h) - \log(20890550 \times 2{\cdot}30285) \\ &= \log(H - h) - 7{\cdot}682215 \end{aligned}$$

Therefore we have

$$\left.\begin{aligned} &\log\cos(C + a - r) = \log\cos(a - r) - x \\ &\qquad \text{where } \log x = \log(H - h) - 7{\cdot}682215 \end{aligned}\right\}$$

Example:—The observed altitude of a mountain peak, 10,000 feet high, was 1° 01′ 30″, the height of the observer's eye being 50 feet and the index error of the sextant (I.E.) − 1′ 30″; required the distance.

Observed altitude - - - - -	1°	01′ 30″
I.E. - - - - - - -		− 1 30
	1	00·0
Dip for 50 ft. from Inman's Tables		− 7·0
Apparent alt. (a) - - - -	0	53·0

In this example, $H - h = 9950$ feet.

$$\begin{aligned} \log 9950 &= 3{\cdot}997823 \\ &\ 7{\cdot}682215 \\ &\ \bar{4}{\cdot}315608 = \log {\cdot}000207 \end{aligned}$$

$$\therefore x = {\cdot}000207.$$

$$\begin{aligned} \log\cos 53' &= \bar{1}\cdot 999948 \\ x &= \phantom{\bar{1}}\cdot 000207 \end{aligned}$$

$$\log\cos(C + 53') = \bar{1}\cdot 999741 = \log\cos 1^\circ\, 58'\cdot 75.$$

$\therefore\ C + 53' = 1^\circ\, 58'\cdot 75 = 118'\cdot 75.$ Therefore $C = 65'\cdot 75.$

With this approximate distance we find, by dividing by 13, that the refraction is $5'$, and consequently the true altitude $(\alpha - r)$ is $48'$.

$$\begin{aligned} \log\cos 48' &= \bar{1}\cdot 999958 \\ x &= \phantom{\bar{1}}\cdot 000207 \end{aligned}$$

$$\log\cos(C + 48') = \bar{1}\cdot 999751 = \log\cos 1^\circ\, 56'\cdot 5.$$

Therefore $C + 48' = 1^\circ\, 56'\cdot 5 = 116'\cdot 5.$

Therefore $C = 68'\cdot 5$, which is the distance required.

If we can estimate the distance of the object observed, either from the reckoning and the chart, or by eye, the refraction obtained from this estimated distance will probably be sufficiently accurate to enable the actual distance to be found directly from the formula.

Case 4.—When the sea or shore horizon can be seen beyond the object, and the height of the observer's eye is considerable, the distance from the object may be found from the observed angle of depression of the water line of the object. Here, as in cases 1 and 2, the distance is necessarily so small that refraction and the curvature of the earth may be neglected.

In Fig. 48, let O be the observer's eye at a height h feet above the sea-level A, and let OS be the apparent direction of the sea or shore horizon.

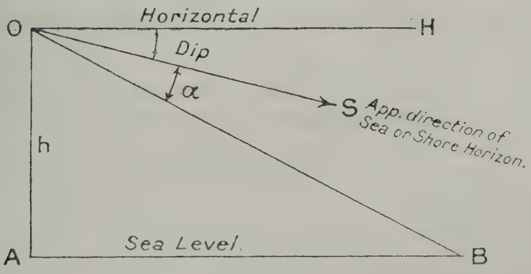


Fig. 48.

Let SOB be the observed angle α between the sea or shore horizon and the water line B of the object.

From the Figure it is clear that the angle $ABO = BOH = \alpha + \text{dip}$. Therefore $AB = AO \cot(\alpha + \text{dip})$.

Therefore, distance $= h \cot(\alpha + \text{dip})$.

60. Lecky's Off-Shore Distance Tables.—These tables give in tabular form the solutions of the trigonometrical equations found in the three cases above.

In Part I. are given solutions of the formula

$$\text{distance} = H \cot \alpha$$

for distances up to 5 miles at every $\frac{1}{10}$th of a mile for heights varying from 50 to 1,100 feet and the corresponding observed angles.

In Part II. are given the solutions of the formula

$$\cos (C + \alpha - r) = \frac{R + h}{R + H} \cos (\alpha - r)$$

for distances varying from 5 miles to 110 miles, and for heights varying from 200 to 18,000 feet and the corresponding observed angles, h being taken as 0.

The finding of distances by means of a vertical sextant angle is, therefore, much simplified by the use of these tables, and as the heights of most prominent peaks, lighthouses, &c. are given on the charts, the method of finding a position line by vertical sextant angle is of very considerable value in navigation. It should be remembered that the heights given on the chart are given above high water of spring tides, and so, when necessary, allowance should be made for the height of the tide at the time of observation. The tables show readily when a small error in the height of the object observed produces appreciable error in the distance.

It should also be remembered, when taking altitudes of lighthouses, that the height of a light given on the chart or elsewhere, is the height of the centre of the lantern and not of the summit of the lighthouse.

When using Lecky's tables for case 1 the error will not exceed the height of the observer's eye if the distance from the shore horizon is greater than the height of the point observed.

When using the tables for case 2 the error will not be appreciable—

(1) if the distance from the shore horizon is greater than the horizontal distance of the shore horizon from the point observed;

(2) if the latter distance is less than the height of the point observed;

(3) if the observed angle is less than 45°.

Now, from the above, it will be seen that the error in each case depends on the height of the observer's eye; therefore in cases where the conditions stated above are not fulfilled and it is still desired to take the observation, it is advisable that the height of eye should be as small as possible.

CHAPTER VIII.

POSITION BY OBSERVATION OF TERRESTRIAL OBJECTS.

61. To fix the position of a ship.—Having shown how a position line may be drawn on the chart, we now have to show how the position of the ship may be found by drawing two or more position lines on the chart. Two or more position lines obtained at the same time give the most satisfactory position, provided that their angles of intersection are not small, and the position so found is called a "fix."

Whenever the position of the ship is fixed, a small circle should be drawn round the position on the chart and the time written against it. When drawing position lines on the chart, unnecessarily long or heavy lines should not be drawn, because they have to be eventually rubbed out and a considerable amount of rubbing out defaces the chart.

62. Position by cross bearings.—When a ship's position is fixed by the intersection of two or more lines of bearing, the position is said to be fixed by cross bearings.

Two objects should be selected, the bearings of which give as near a right-angled cut as possible. The bearing of a third object should be taken when possible, not only because it is a check on the observations, but because it ensures us against the possibility of laying off a position line from the wrong point.

Objects abeam and before the beam should be used in preference to objects abaft the beam which the ship has already passed.

Objects should be selected that are near to the ship, in preference to those far away, because any error in the bearing of a near object has less effect on the position than the same error in the bearing of a distant object; and moreover, as charts are slightly distorted in printing, long lines of bearing are never so accurate as short ones.

When taking cross bearings the names of the objects should first be written in the note-book, after which the bearings should be observed as quickly as possible with due regard to accuracy—the object whose bearing is changing most rapidly being observed last. The bearings should be written against the names of the objects in the note book; the time of the fix, which should be that at which the last bearing was observed, should also be noted. Should the objects be changing their bearings quickly, it is impossible to get a satisfactory cut if some time elapses between taking the bearings of the different objects.

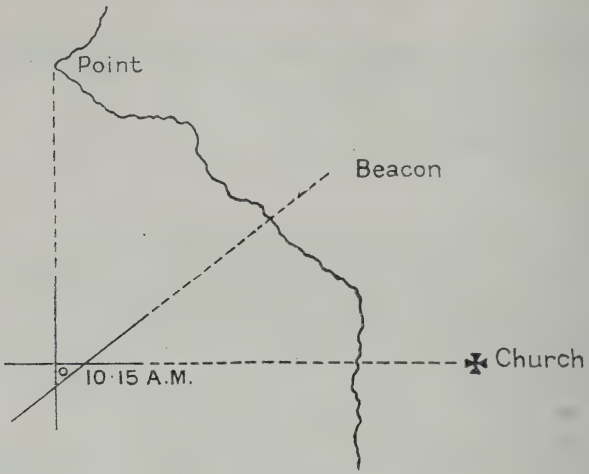


Fig. 49.

When, owing to small errors of observation or to the points observed being incorrectly placed on the chart, the three lines of bearing do not intersect at a point, the small triangle formed is called a cocked hat, and in this case the central point of the cocked hat should be taken as the position of the ship, as shown in Fig. 49.

When it is known that the cocked hat is due to an incorrect deviation having been used, or, in other words, to all three lines of bearing having the same error, it is possible to give a geometrical construction for finding the position of the ship, but it is better to obtain the two horizontal angles subtended by the objects by means of the differences of their bearings and to plot the position of the ship with the aid of the station-pointer as explained in § 65.

63. Position by bearing and horizontal sextant angle.—It may happen that only one conspicuous object can be observed from the standard compass. In this case a fix can often be obtained by taking a bearing of that object, and at the same time observing the sextant angle between it and some other object from a position near the standard compass.

Thus in Fig. 50, if a bearing is taken of B and the horizontal sextant angle α subtended by BC is measured, then the observer is at the intersection of the line of bearing AB and the segment of the circle BAC which contains the angle α. In practice it is not usual to draw the segment of the circle, because the intersection of the position lines can be more rapidly found as follows.

If the horizontal sextant angle α is applied to the observed bearing of *B*, the bearing of *C* is obtained and the position may be plotted by cross bearings.

In Fig. 50, the Hill bore N. 30° E. and the angle to the Church is 45°. As the Church is to the right of the Hill, the bearing of the former must have been N. 75° E.

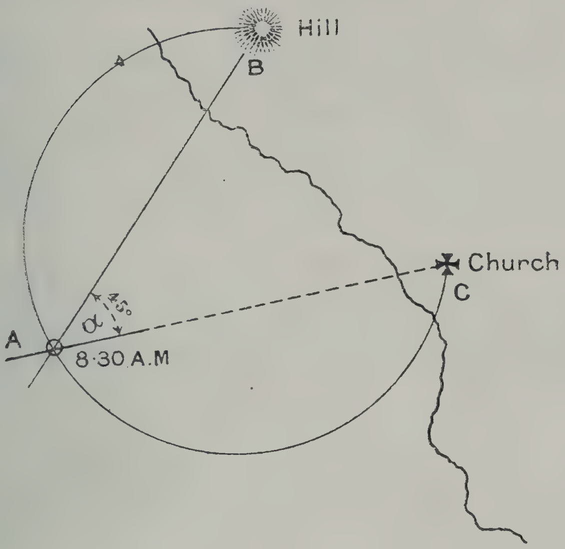


Fig. 50.

The position of the ship is therefore at *A*, which is the point of intersection of the lines of bearing.

When selecting the object *C* it is advisable that the observed angle should be as nearly 90° as possible, and in no case less than 25°; when possible a second angle or bearing should be obtained as a check, because any error in either the bearing or the angle would not otherwise be apparent.

When two objects are seen to be in line with one another they are said to be in transit, generally denoted by ϕ, so that when an observer sees two objects in transit, and these objects are marked on the chart, his position line is the straight line which passes through the two objects.

When cruising in narrow waters or near land, care should always be taken to note the transits of any conspicuous objects, since a transit by itself gives a position line. At the moment of the transit coming on, if the bearing of, or an angle to, some other object situated so as to give as near a right-angled cut as possible, be taken, a good fix is obtained, provided that the distance apart of the objects in transit is sufficient to render the transit a sensitive one, as explained in Part II.

As before, check angles or bearings should be taken when possible.

64. Position by bearing and distance.—When only one object is in sight, if we can obtain its distance, either by rangefinder or by vertical sextant angle, as explained in §§ 50 and 59, and at the same time take its bearing, the position of the ship must be at the intersection of the line of bearing and the circle described with the object as centre and the distance as radius. This is an exceedingly useful method of fixing the position of the ship quickly.

65. Position by horizontal sextant angles.—The method of fixing the ship's position by the intersection of two or more position lines, obtained by observing the horizontal sextant angles subtended by three or more objects, is extremely useful in navigation when great accuracy is essential or when no compass is available, as the observations can be taken from any position in the ship.

The position is more exact than the position found by bearings, because the angles can be measured with a sextant with greater precision than the compass will permit. This method is especially valuable when the objects available are at a considerable distance from the observer, when the drawing of long lines of bearing introduces error which is difficult to avoid. Another advantage is that the observer is not tied to any one spot, and can therefore place himself in the most advantageous position to see the objects clear of masts or other obstacles which ordinarily obscure so many points.

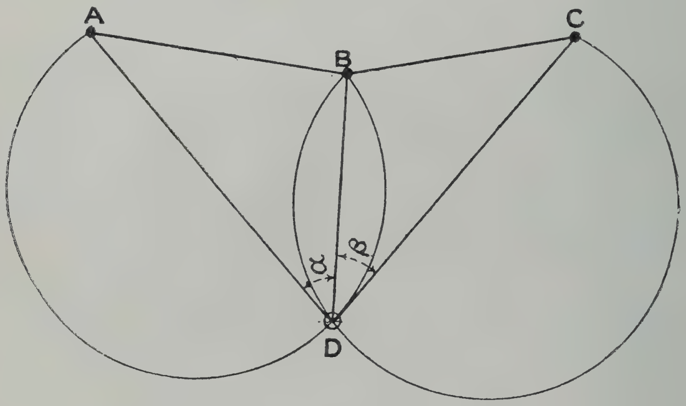


FIG. 51.

In Fig. 51, let A, B, C be three objects, and let the horizontal sextant angles subtended by AB and BC be α and β respectively; then the observer is at the point D which is the intersection of the three position lines corresponding to the angles α, β, and $(\alpha+\beta)$; the segment of the circle corresponding to the angle $(\alpha+\beta)$ is not shown in the figure.

The drawing of the circles is a matter which occupies some time, and requires great care when accuracy is desired; but tracing paper on which the angles may be plotted, or preferably the station-pointer, affords the means of ascertaining the position readily, quickly, and accurately, provided that the angles of intersection of the circles are not less than 60°.

The station-pointer, which is described in Part IV., consists of three legs, two of which are movable, radial to a common centre, with an arrangement for setting them at the required angles from the central fixed leg. The right leg being set for the angle measured between *C* and *B* and the left leg to that between *B* and *A*, the instrument should be placed on the chart with the chamfered edge of the central leg directed to *B*, and the instrument moved until the chamfered edge of the right leg falls on *C* and that of the left on *A*. The centre of the instrument will then be on the position where the two circles, if drawn, would intersect, because from no other position would all the legs, when set at the proper angles, coincide with the objects. A dot made with a sharp pencil at the centre of the instrument marks the position of the ship.

It is important to so select the objects that the circle passing through them does not pass through or near the position of the ship. Should the circle pass through the position of the ship, it will be seen from Fig. 52 that, since angles in the same segment of a circle are equal to one another, the ship might be situated at *X* or *Y* or at any point on the segment of the circle, for at every point on this segment the angles between Rock and Tower and between Tower and Lighthouse are the observed angles α and β respectively.

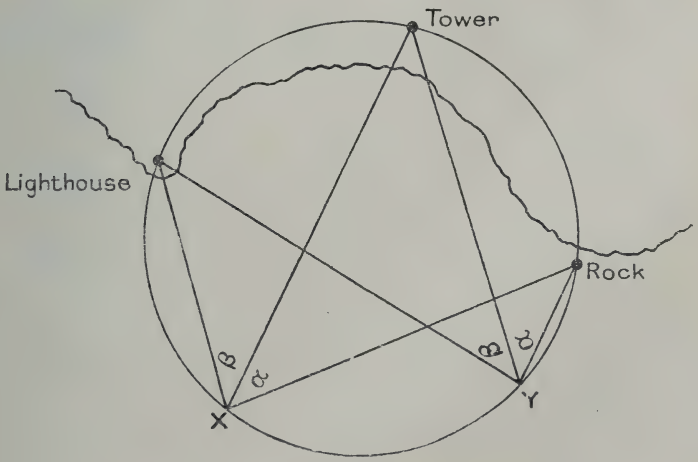


Fig. 52

By attending to the following rules this may be avoided.

(1) *The middle object may be on the ship's side of the line joining the other two, as shown in Fig.* 53.

If the central object is very close to the ship, the method should not be employed unless the whole angle between the right and left objects can be observed, and then either the right or left angle, because the angles adjoining the central object are changing very quickly as compared with the whole angle.

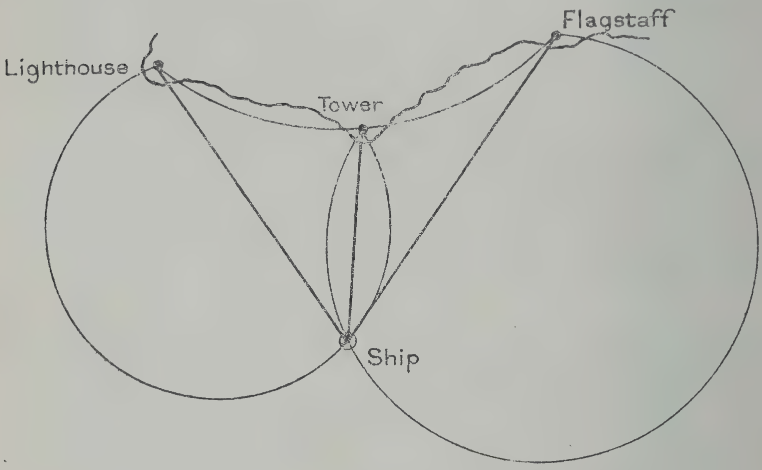


Fig. 53.

(2) *The three objects may be in or near a straight line as shown in Fig.* 54.

In this case the angles observed should not be too acute—that is, neither of the angles should be less than 30°.

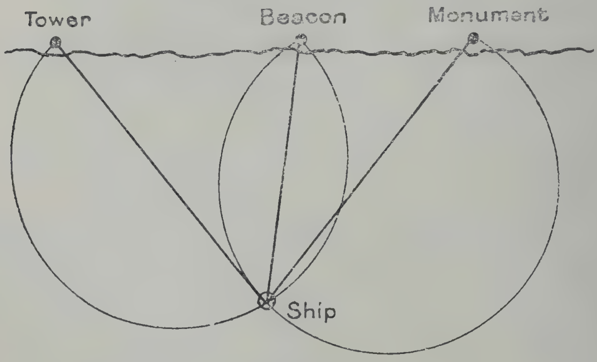


Fig. 54.

(3) *The ship may be inside the triangle formed by the three objects, as shown in Fig.* 55.

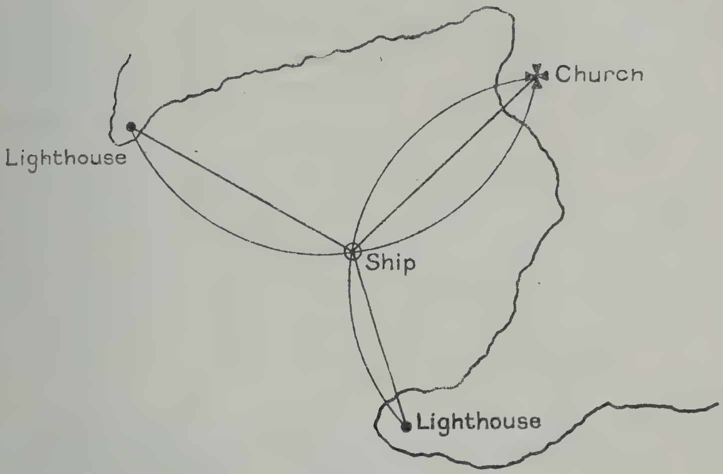


Fig. 55.

In all doubtful cases, either a bearing should be taken of one of the objects, or a check angle should be taken to a fourth object.

When a check angle is taken, it should always be taken from the central object to a fourth object, and if a second check angle is taken, it should be taken from the central object also. This facilitates plotting, because, after having placed the legs of the station-pointer on the three original objects, the centre of the instrument and the fixed leg can be held steady, and one or both of the movable legs can be moved to show the check angle or angles.

When writing down a station-pointer fix, the names of the objects should be written from left to right, as they were situated when observed, and the check angle written below.

For example :—

Lighthouse 10° 15′ Beacon 85° Church
,, 50° Flagstaff.

which indicates :—

Left-hand angle between beacon and lighthouse	10° 15′
Right-hand angle between beacon and church -	85° 00′
Check angle between beacon and flagstaff (to right of beacon) - - - -	50° 00′

When plotting with a station-pointer, if the objects were well placed according to the foregoing rules, the slightest movement of the centre of the instrument will immediately throw out one or more of the legs. Conversely, when the centre of the station-pointer can be moved without the legs being thrown off the objects, it indicates that the objects are badly placed and the fix unreliable.

As a general rule, the greater the difficulty in plotting the position with a station pointer, to a person accustomed to its use, the more unreliable is the fix.

The station-pointer should not be used on charts which indicate, as explained in Part II., that the survey was not made in great detail. In such a case it is preferable to fix by cross bearings. If bearings of several objects are observed, and the lines of bearing do not intersect at a point, it shows that one or more of the objects is incorrectly charted or that an error was made in the observation of one or more of the bearings.

Where the distances, as represented on the chart, are very small, it frequently happens that the central part of the instrument obscures one or more of the points observed: in such a case it is convenient to plot the angles on either a Douglas' protractor, a Cust's station-pointer, or a piece of tracing paper and to use it in the same manner as the station-pointer. The Douglas' protractor and the Cust's station-pointer are graduated celluloid sheets on which lines may be drawn.

66. Running fix.—We have shown above how the ship's position may be found by the intersection of position lines from simultaneous observations, and we have now to show how the position may be obtained when only one object is in sight whose distance we do not know. This is done by obtaining two position lines from two observations with a considerable interval of time between them, the position so found being called a "running fix."

The value of a running fix is manifestly dependent on the accuracy of the reckoning kept, and on the correct estimation of the tidal stream or current experienced during the interval; for this reason, it is desirable when possible to obtain absolute fixes.

A running fix depends on the following principle. In Fig. 56, suppose the ship to be at any point P on the position line AB, and suppose that in a given time she steams a given course and distance represented by the line PP' to P'.

Again, suppose the ship to be at Q on the position line AB, and that in the same time she steams the same course and distance represented by QQ' to Q', then the line $P'Q'$ is parallel to AB.

From this we see that, wherever the ship may be on the line AB, she will, after steaming the given course and distance,

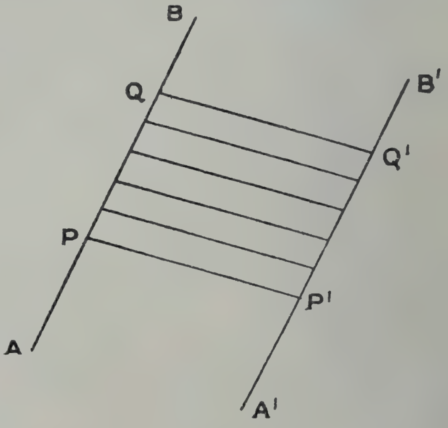


Fig. 56.

be on the line $A'B'$. This line is called the *first position line transferred* to the time of the second observation.

Every running fix may be plotted as follows:—

(1) Draw the first position line on the chart.
(2) From any point on the first position line lay off the course and distance run between the observations, and from the extremity of this line the estimated direction and amount of the current or tidal stream in the interval.
(3) Through the point so found draw a line parallel to the first position line; this is the first position line transferred, and the ship must be situated somewhere on this line provided the course and distance made good between the observations has been correctly estimated and laid off.
(4) Draw the second position line on the chart; the point at which this line cuts the first position line transferred is the position of the ship.

Example:—Ship's course East, 8 knots.
Estimated current, S.E., 3 knots.
At 4^{h} P.M. the lighthouse bore N. 34° E.
At 4^{h} 30^{m} P.M. the lighthouse bore N. 22° W.

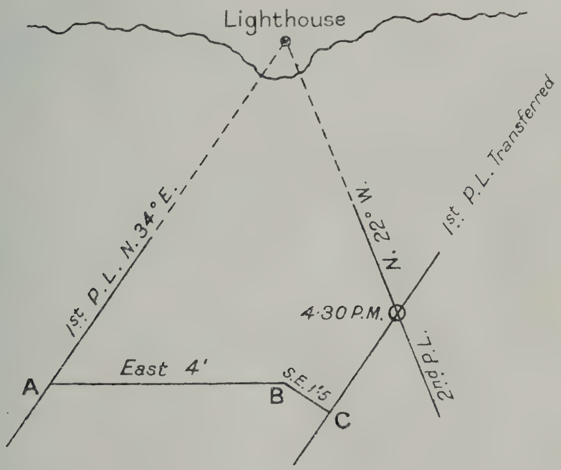


Fig. 57.

In Fig. 57, A is any point on the first position line.
AB is the course and distance run in 30 minutes.
BC is the direction and amount of the current in 30 minutes.
The position at 4^{h} 30^{m} P.M. is as shown in the Figure.

In this example, two bearings of the same object have been taken with which to obtain the position lines; but the same method holds good if two different objects have been observed, in either case the difference in bearing should exceed 25°.

A special case of this problem is called fixing by doubling the angle on the bow. By the angle on the bow is meant the angle at the observer between the ship's course and the direction of the object; it is measured from right ahead to starboard or port, from 0° to 180°.

In Fig. 58 it will be seen that the distance of the observer from the object when the angle on the bow has been doubled is equal to the distance run over the ground in the interval.

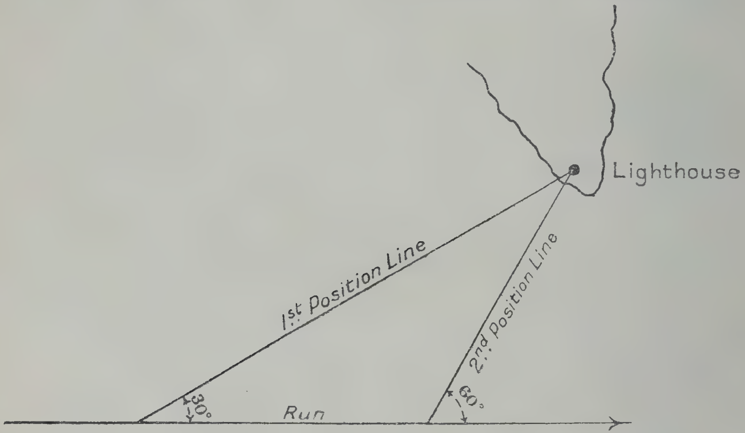


Fig. 58.

When the first angle observed is 2 points ($22\frac{1}{2}°$), the distance of the object when abeam is the distance run multiplied by ·7.

The position by four point bearing is another special case when the first bearing is 4 points on the bow, and the second when the object is on the beam.

The method of fixing by doubling the angle on the bow should not be employed when there is a tidal stream or current whose direction is not the same as the ship's course, or contrary to it; therefore, in general, when there is a tidal stream or current. the fix should be plotted as an ordinary running fix.

67. Use of soundings in obtaining the position.—When only one object is in sight, an approximate position can be obtained by observing the bearing of the object and taking a sounding at the same time. The sounding must be reduced to the level or datum to which soundings on the charts are reduced, and, if a chemical tube has been used, should be corrected for the height of the barometer as explained in Part IV.

Little reliance can be placed on this fix unless the soundings shown on the chart are such that the fathom line of the depth obtained can be drawn with confidence, its mean direction makes a good angle with the line of bearing, and the depth has been verified by two or more soundings.

It is sometimes possible to estimate the ship's position approximately as follows:—

Sound at regular intervals, noting the depth and nature of the bottom at each sounding; these soundings must be corrected as mentioned above.

Draw a few lines on a piece of tracing paper to represent true meridians, and on it lay off the course made good (allowing for tidal streams or currents). On the line which represents the ship's track, plot the observed soundings and natures of the bottom at their correct distances apart, according to the scale of the chart.

Place the tracing paper on the chart in the vicinity of the ship's estimated position, and, keeping the meridians drawn on it parallel to those on the chart, move it about and see if the soundings on the tracing paper can be made to coincide with those on the chart. If they do coincide, the position of the ship at the time of the last sounding was at the point of the chart underneath the last sounding on the tracing paper.

The utmost caution should be observed in estimating the ship's position from the coincidence of a line of soundings with the soundings on the chart, because small errors may give very erroneous results particularly where the water shoals gradually.

CHAPTER IX.

THE HEAVENLY BODIES AND THEIR TRUE PLACES.

68. Necessity for astronomical observations.—As stated in § 47, the position of the ship should be frequently determined by observation, not only as a check on the accurate steering of the course and on the estimated speed, but also to guard against a wrong estimation of currents, tidal streams, &c. When it is impossible to determine the ship's position by observations of fixed objects on shore, as, for instance, when there is a haze over the land, or when the ship is in mid ocean, we have to find it by observation of the heavenly bodies; but before proceeding to explain how this may be done, it is necessary to give some account of the heavenly bodies, with special reference to those which are suited to the purposes of navigation.

The heavenly bodies may be classified into two groups, the stars and the solar system.

69. The stars.—The stars are bodies comparable in size and physical conditions with the sun, shining by their own light as does the sun, and emitting a radiance which cannot be distinguished from sunlight. Some of the stars are much larger than the sun and some are much hotter, some are smaller and some cooler.

70. The constellations.—In ancient times the stars were grouped into constellations, partly as a matter of convenient reference, and partly as superstition. These groups were given fanciful names, mostly of persons or objects conspicuous in the mythologies of the times. In some cases a vague resemblance to the object which gives the name to the constellation can be traced, but generally it is difficult to assign a reason as to why the constellations have been so named or so bounded.

The names of the constellations are given in a Latinised form, such as Leo, Taurus, Argus, &c.

71. Designation of bright stars.—The stars in a particular constellation are designated by letters of the Greek alphabet, assigned usually in order of brightness. Thus the brightest star in the constellation Taurus, is α Tauri, the next brightest star is β Tauri, and so on. Some of the bright stars have names of their own, the majority of the names being of Greek or Latin origin, as, for instance, Arcturus (α Boötis), and Procyon (α Canis Minoris); some, however, have Arabic names, as, for instance, Aldebaran (α Tauri).

72. Magnitudes of stars.—The term "magnitude," as applied to a star, refers simply to its brightness. The magnitudes of the stars have been determined on the assumption that the magnitude of a particular star, called the Pole star, is 2·15.

Magnitudes are assigned to stars according to their brightness, the brighter the star the smaller being the number assigned to its magnitude.

Those stars whose magnitudes are less than 2 are called stars of the 1st magnitude, those whose magnitudes are 2 and above but less than 3 are called stars of the 2nd magnitude, and so on.

Those stars which can only just be seen by the naked eye on a clear night are stars of the 6th magnitude.

73. The Solar System.—If we now confine ourselves to that particular star which is called the sun, we find that there are several bodies which revolve round it in definite periods. These bodies are called the sun's planets, and one of them is the earth. For the purposes of navigation, we need only consider five of the planets, namely, Venus, The Earth, Mars, Jupiter and Saturn.

The planets revolve round the sun in planes which are little inclined to one another, and they have a common direction of revolution which is the same as that of the earth on its axis. They have also a common direction of rotation on their axes, which is the same as that of the sun.

The earth moves round the sun in an orbit which is an ellipse, the plane of the ellipse being inclined at an angle of about 23° 27′ to the plane of the earth's equator.

In the same way as the earth revolves round the sun, so the moon revolves round the earth, the plane of the moon's orbit being inclined at about 5° to that of the earth. The moon is called the Earth's satellite. Similarly Mars, Jupiter, and Saturn are attended by their respective satellites in their motion round the sun, and, in addition to satellites, Saturn is surrounded by three revolving rings.

The following table gives details of the sun, planets, and the moon, which, together with other bodies which are of no value in navigation, form what is called the Solar System :—

——	Sun.	Venus.	The Earth.	Moon.	Mars.	Jupiter.	Saturn.
Mean distance from sun, in millions of miles.	—	67	92·7	—	141	482	884
Diameter in statute miles.	865,000	7,660	7,918	2,163	4,200	85,000	71,000
Time of axial rotation.	25·3 days.	23h. 21m.	23h. 56m.	—	24h. 37m.	9h. 55m.	10h. 14m.
Time of orbital revolution in years.	—	·62	1	—	1·88	11·86	29·46
Inclination of orbit to the equator.	—	—	23° 27′	—	24° 50′	3° 05′	26° 49′
Number of satellites.	—	—	1	—	2	4	8 and 3 rings.
Densities -	—	·92	1	·613	·45	·23	·11
Inclination of orbit to the ecliptic.	—	3° 23′	0	—	1° 51′	1° 18′	2° 29′

The mean distance of the moon from the earth is 239,000 statute miles.

74. The Nebular Theory.—It is so important to realise the rapid movements of the moon and planets in distinction to the comparative fixity of the stars, that in order to emphasise the matter a brief account of the nebular theory of Laplace may not be without value.

Laplace supposed that the matter now condensed into the various members of the solar system once formed a vast nebula of intensely heated gas. This nebula under the action of universal gravitation assumed an approximately globular form with rotation about an axis.

This rotation may be accounted for by supposing that different portions of the nebula had motions of their own; then, unless these motions happened to be balanced in the most perfect and improbable manner, a motion of rotation would set in of itself as the nebula contracted.

The principle of the conservation of momentum shows that, as the nebula contracted, its angular velocity must have increased. In consequence of the rotation, the mass became flattened at the poles, instead of remaining spherical.

As the speed of rotation increased, the centrifugal force increased, particularly in the equatorial regions, till a time arrived when the centrifugal force became equal to gravity, and rings of nebulous matter, resembling the rings of Saturn, were thrown off; in other words, the augmenting centrifugal force from time to time prevented the equatorial zone from following any further the contracting mass, and so the zone remained behind as a revolving ring.

Each of the revolving rings, thus periodically detached, eventually broke up into many masses which finally combined to form a single planet.

A detached planet, in like manner to the parent mass, increased in speed of rotation as it decreased in size, and, where the centrifugal force was sufficient, similarly left rings behind which finally collapsed into rotating bodies, called satellites. Thus out of the detached rings there arose planets and satellites, while the remains of the central mass exists in the sun.

Of course there are several anomalies in the theory sketched above, particularly if we consider all the planets and satellites of the solar system, but, on the whole, the facts give support to it.

The planets are bodies which have cooled down to such an extent as to give little or no light of their own, and are seen by the light of the sun reflected from them to the earth's surface.

The planets, therefore, are unlike the stars in two respects.

Firstly, they are in motion, while the stars are relatively fixed.

Secondly, they are seen by the sun's reflected light, while the stars are seen by their own light.

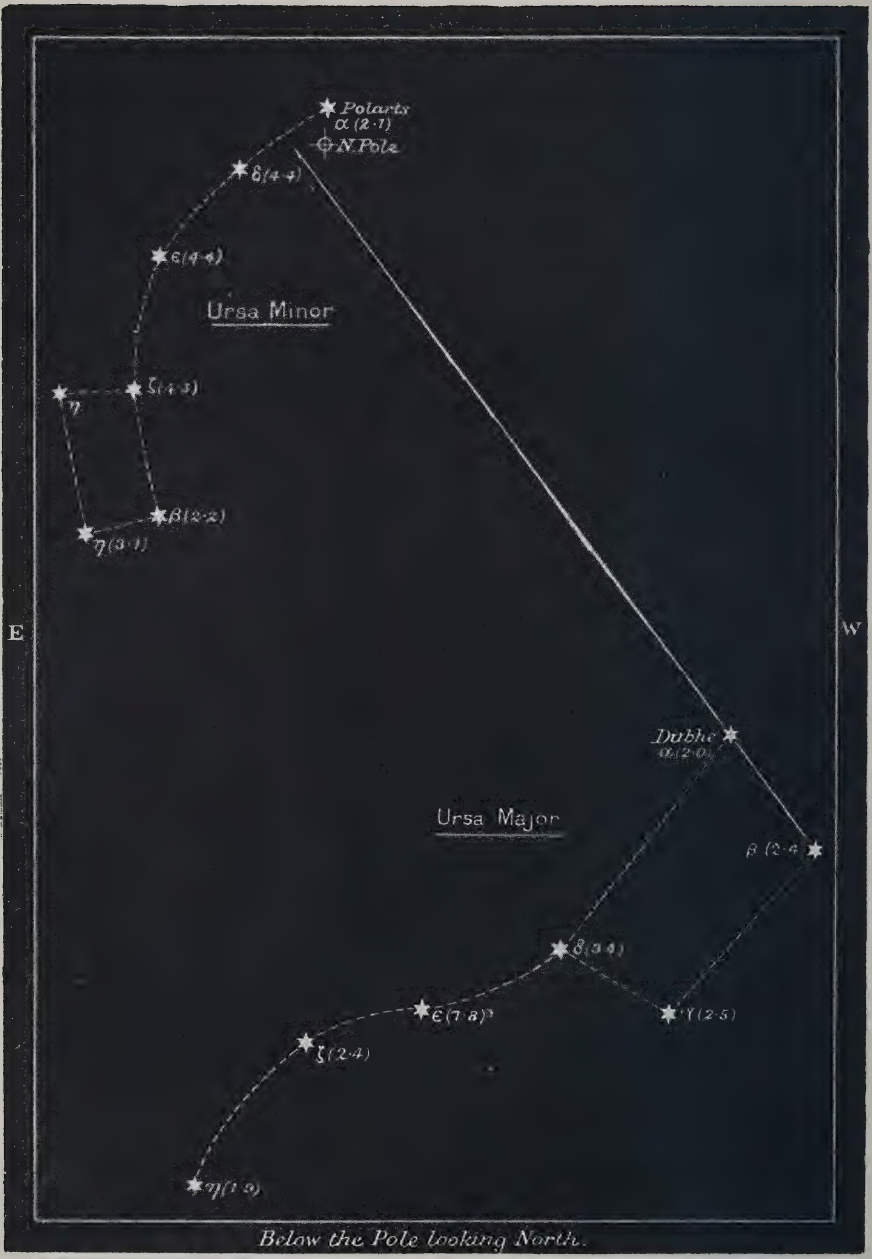

Polaris
α (2·1)
N. Pole
δ(4·4)
ε(4·4)
Ursa Minor
ζ(4·3)
η
β(2·2)
η(3·1)
E
W
Dubhe
α(2·0)
Ursa Major
β (2·4)
δ(3·4)
ε(7·8)
γ(2·5)
ζ(2·4)
η(1·9)
Below the Pole looking North.

Fig. 59.

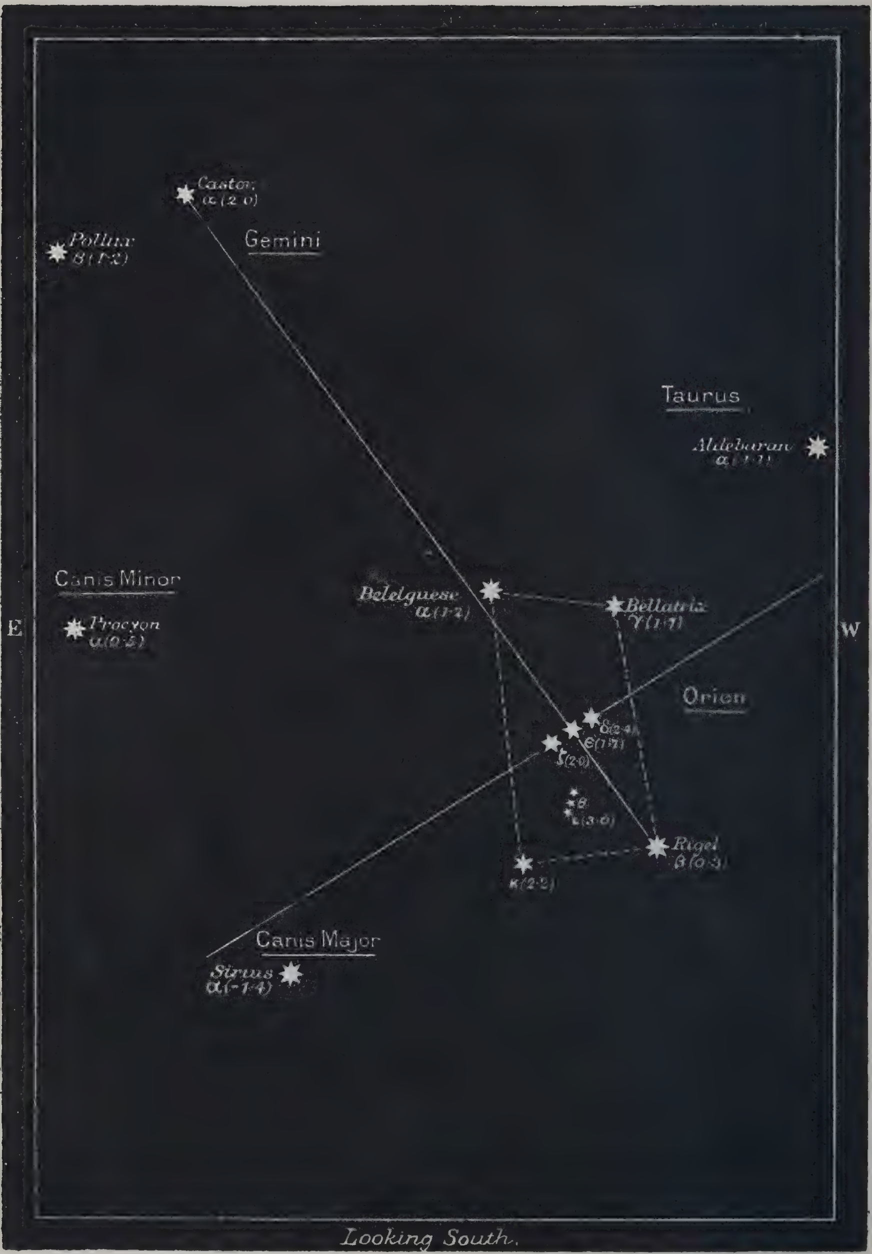

Castor
α(2·0)
Gemini
Pollux
β(1·2)
Taurus
Aldebaran
α(1·1)
Canis Minor
Procyon
α(0·5)
E
W
Belelguese
α(1·2)
Bellatrix
γ(1·7)
Orion
δ(2·4)
ε(1·7)
ζ(2·0)
θ
ι(3·0)
Rigel
β(0·3)
κ(2·2)
Canis Major
Sirius
α(-1·4)
Looking South.

Fig. 60.

The planets can generally be distinguished from the stars by remembering that they shine with a steady light, while most of the stars twinkle.

It will be seen from the table given in § 73 that the orbit of Venus lies between the earth and the sun; for this reason Venus is called an inferior planet, and, because it is always close to the sun, is only seen in the morning or evening.

75. How to recognise the stars.—Most of the important stars can be recognised by referring them to imaginary lines in the heavens, indicated by the principal stars in such well-known constellations as the Great Bear (Ursa Major) and Orion, the names and appearances of which should be first studied.

Fig. 59 shows the constellations known as the Great Bear (Ursa Major) and Little Bear (Ursa Minor).

Pole-star or Polaris (α Ursæ Minoris).—A line from β Ursæ Majoris through α Ursæ Majoris (Dubhe) points to the Pole star. For this reason α and β Ursæ Majoris are often spoken of as the pointers.

Arcturus (α Boötis) and Spica (α Virginis).—Arcturus is a very bright star, and is found by continuing the curve of the tail of the Great Bear. If this curve is continued still further it will pass through Spica, Arcturus being about midway between the tail of the Bear and Spica.

Denebola (β Leonis).—Denebola forms with Arcturus and Spica an equilateral triangle.

Capella (α Aurigæ).—Capella lies on a line drawn from the Pole-star at right angles to the line joining the pointers, away from the Little Bear, and at a distance of about 45°. Near Capella there are three fairly bright stars which form an isosceles triangle.

Vega (α Lyræ).—Vega is found by extending the line joining Capella to the Pole-star to about an equal distance on the opposite side of the pole. Near Vega there is a very distinct W of small stars.

Fig. 60 shows the constellation of Orion and some of the bright stars near it. This constellation is always very conspicuous, and, owing to the large number of bright stars in its vicinity, is especially useful for pointing out the other stars in the heavens. Four of the stars in this constellation are at the corners of a quadrilateral, three of them being stars of the 1st magnitude, namely, Betelguese (α Orionis), Rigel (β Orionis) and Bellatrix (γ Orionis), the other is a star of the 2nd magnitude (κ Orionis).

In the middle of the quadrilateral there are three stars situated in a straight line and very close to one another: these three stars are called Orion's belt.

Sirius (*α Canis Majoris*), *and Aldebaran* (*α Tauri*).—In the Figure it will be seen that Orion's belt points in one direction roughly towards Sirius, and in the other roughly towards Aldebaran, and that these stars are approximately equidistant from the belt. Sirius has a magnitude of $-1{\cdot}4$, and is the brightest star in the heavens. Aldebaran may be distinguished by its reddish tint.

Canopus (*α Argus*).—Canopus is about 36° S. 5° W. from Sirius, and has a magnitude of $-1{\cdot}0$, being next to Sirius in brightness.

Pollux (*β Geminorum*) *and Castor* (*α Geminorum*).—A line from Rigel through the middle star of Orion's belt points to Castor, and Pollux will be found not far away.

Procyon (*α Canis Minoris*).—Procyon forms, with Sirius and Betelguese, an equilateral triangle.

Regulus (*α Leonis*).—A line from Bellatrix through Betelguese points towards Regulus, which is about 60° from Betelguese.

Fig. 61 shows the constellations of Pegasus and Cassiopeia, and other stars in the vicinity.

Markab (*α Pegasi*).—It will be seen in the Figure that this star is the South-Western star of the square of Pegasus, and the two Western stars of the square point to the Pole-star.

Fomalhaut (*α Piscis Australis*).—The line joining the two western stars of Pegasus, produced away from the Pole-star, passes through Fomalhaut.

Altair (*α Aquilæ*).—Altair lies between two less brilliant stars in a line with Vega; a line from Capella through γ and β Cassiopeiæ points to Altair.

Antares (*α Scorpii*).—Antares is a reddish star, and is at the centre of a small bow which points directly at another bow.

Achernar (*α Eridani*).—Achernar lies on a line joining Canopus and Fomalhaut, and is midway between them.

Fig. 62 shows the Southern Cross, in which α, β and γ Crucis are all stars of the 1st magnitude; α and β Centauri, which are very bright stars of the 1st magnitude, are also shown in the Figure. It should be noticed that β Centauri is nearer to the Southern Cross than α Centauri.

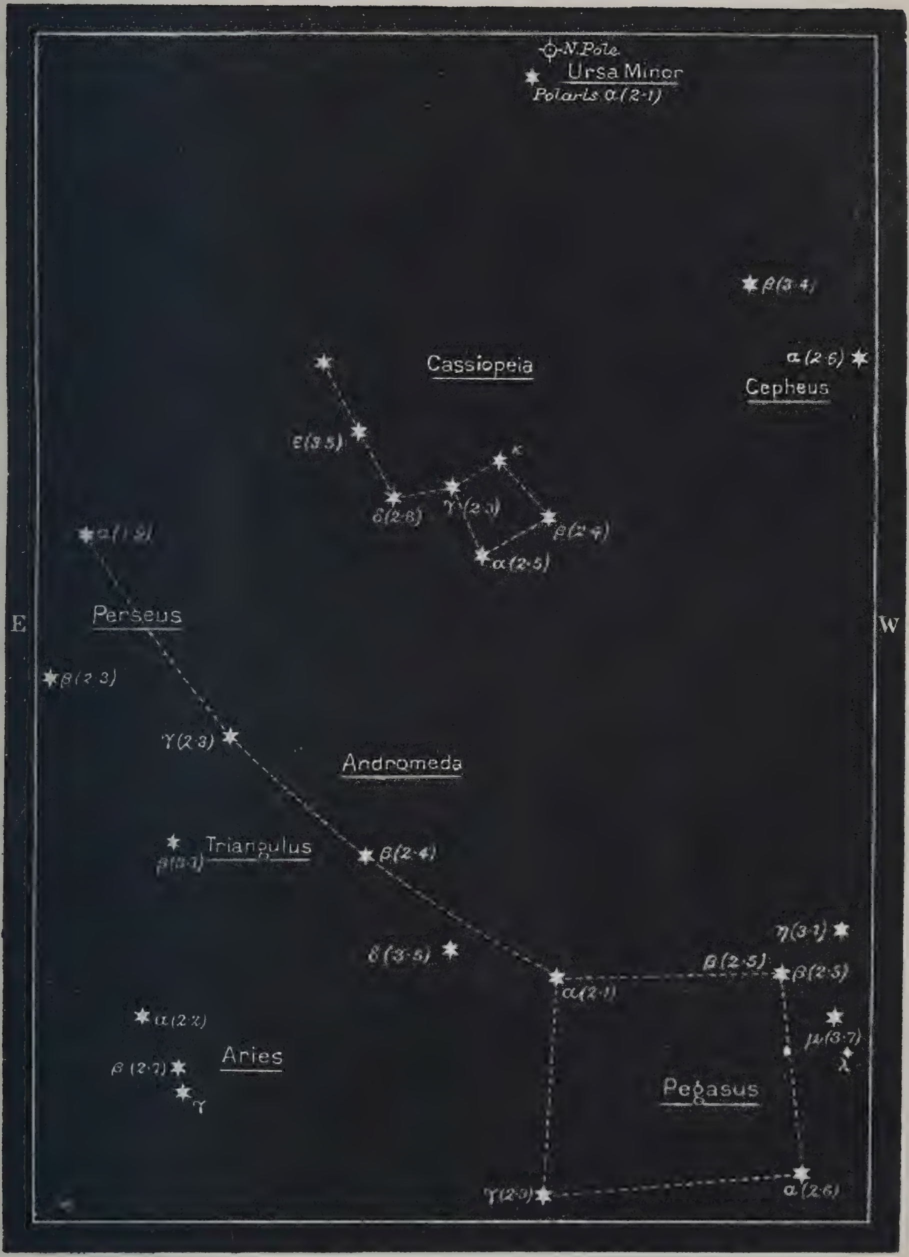

N.Pole
Ursa Minor
Polaris α (2·1)
β (3·4)
α (2·6)
Cassiopeia
Cepheus
ε (3·5)
κ
γ (2·3)
δ (2·8)
β (2·4)
α (2·5)
α (1·9)
Perseus
E
W
β (2·3)
γ (2·3)
Andromeda
Triangulus
β (3·1)
β (2·4)
η (3·1)
δ (3·5)
β (2·5)
β (2·5)
α (2·1)
μ (3·7)
λ
α (2·2)
Aries
β (2·7)
γ
Pegasus
γ (2·9)
α (2·6)

Fig. 61.

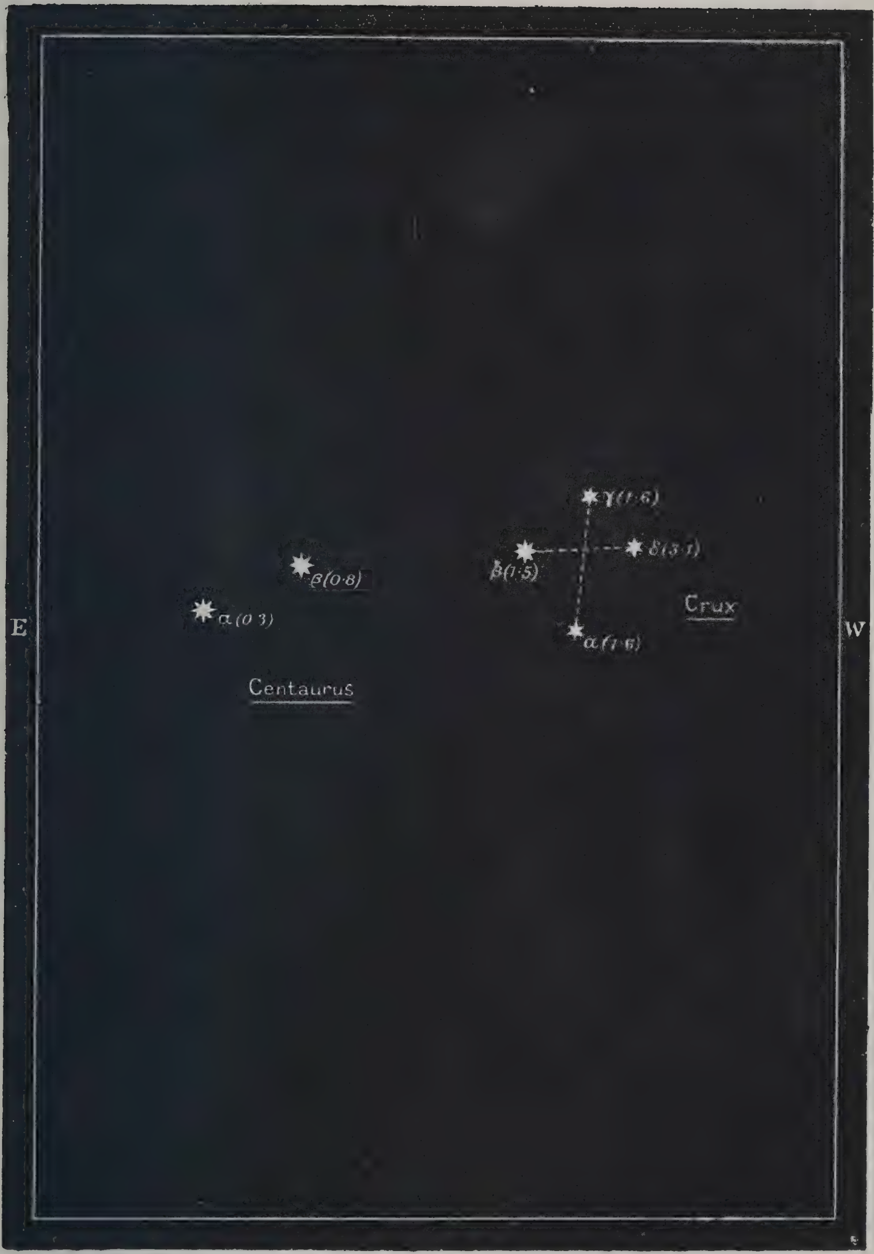


Fig. 62.

38739.405. W B & L. 12/1/15.

76. The movement of the earth.—In Fig. 63, S represents the sun, and E_1, E_2, E_3 and E_4, the positions

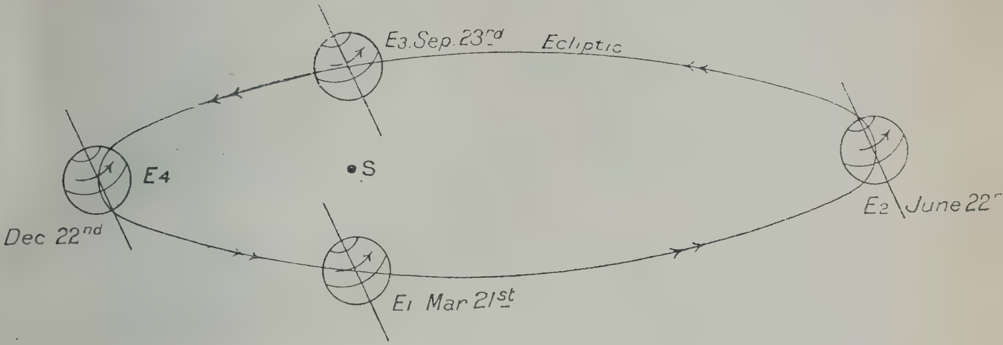


Fig. 63.

of the earth at the commencement of the seasons spring, summer, autumn, and winter respectively; the observer is supposed to be looking down from the North side of the plane of the orbit, which is an ellipse, the earth when at E_4 being about three million miles nearer to the sun than when at E_2. The axis of the earth is not at right angles to the plane of the orbit, but inclined to it at an angle of about 66° 33′; therefore the plane of the equator and that of the orbit are inclined to one another at an angle of about 23° 27′.

As the earth, during its revolution round the sun, rotates on its axis, any spot on the earth's surface is exposed alternately towards the sun and away from it; the time during which the sun is visible is called day, and that when the sun is obscured is called night.

The earth makes a complete revolution round the sun in a year.

77. The celestial concave. The ecliptic and celestial equator.—The observer, being unable to judge the

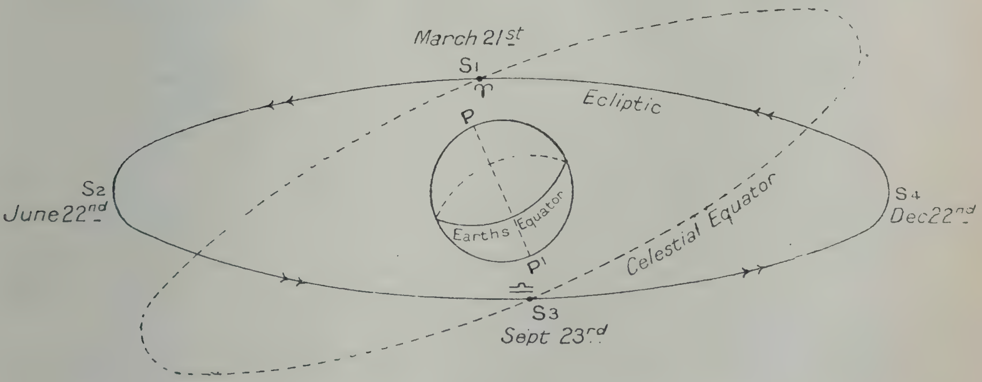


Fig. 64.

relative distances of the heavenly bodies, sees them apparently on the interior surface of an infinitely large sphere, of which his eye is the centre. This sphere is called the celestial concave and the points where it is intersected by the earth's axis produced are called the celestial poles. That pole which is above the horizon is called the elevated pole.

From the point of view of the earth being stationary and the sun revolving round it once a year, it is convenient to compare Fig. 64, drawn on this supposition, with Fig. 63, which illustrates the true case. In Fig. 64, S_1, S_2, S_3 and S_4 are the apparent places of the sun as really seen from E_1, E_2, E_3 and E_4 respectively.

Owing to the real movement of the earth in the direction of the double arrows, Fig. 63, the centre of the sun appears, in the course of a complete revolution (year), to describe a circle on the celestial concave, Fig. 64; this circle is called the ecliptic.

Since the planes of the orbits of the moon and planets are but little inclined to that of the ecliptic, the moon and planets are always seen near the ecliptic. An imaginary belt of the heavens, extending 8° on either side of the ecliptic and in which all the planets are situated, is termed the zodiac.

The plane of the earth's equator, if extended, would intersect the celestial concave in a great circle, which would intersect the ecliptic in two opposite points. This great circle on the celestial concave is called the celestial equator (or equinoctial), and is evidently inclined to the ecliptic at the same angle as the plane of the earth's equator is inclined to that of its orbit; this angle ($23° 27'$) is called the obliquity of the ecliptic.

The axis of the earth remains, for all practical purposes, parallel to itself during every revolution; therefore the two opposite points of intersection of the ecliptic and celestial equator are practically fixed points on the celestial concave. They are known as the first points of Aries and Libra, because in early ages they occupied positions in these constellations. On March 21st, when the earth is at E_1, the centre of the sun occupies on the celestial concave the same apparent position as the first point of Aries, and this position is called the vernal equinoctial point; for a similar reason, when the earth on September 23rd is at E_3, the sun apparently occupies the first point of Libra, and this position is called the autumnal equinoctial point. Therefore, the first point of Aries is the position of the sun on the celestial equator as it moves from South to North; it is denoted by the symbol ♈, Fig. 65.

A difficulty may occur to the reader that the plane of the equator when the earth is at E_2, Fig. 63, is not identical with that when the earth is at E_4, and that, therefore, the points of intersection of the plane of the equator with the fixed plane of the ecliptic are not the same in the two cases. This is strictly true, and would be appreciable at a finite distance, but is not so at the infinite distance of the celestial concave. The celestial poles being at an infinite distance are unaffected by the earth's motion in its orbit, and may, therefore, be regarded as fixed points.

The ecliptic and celestial equator intersect at the equinoctial points, and are, therefore, most widely separated at positions midway between these points. These positions are known as the summer and winter solstitial points, and the sun appears to occupy them when the earth is at E_2 (June 22nd) and at E_4 (December 22nd), respectively.

78. Positions of heavenly bodies.—The celestial equator being a fixed circle on the celestial concave, and the first point of Aries very nearly a fixed point on that circle, the positions of the heavenly bodies may be expressed by reference to them, in precisely the same way as places on the earth's surface are expressed by reference to the equator and the meridian of Greenwich.

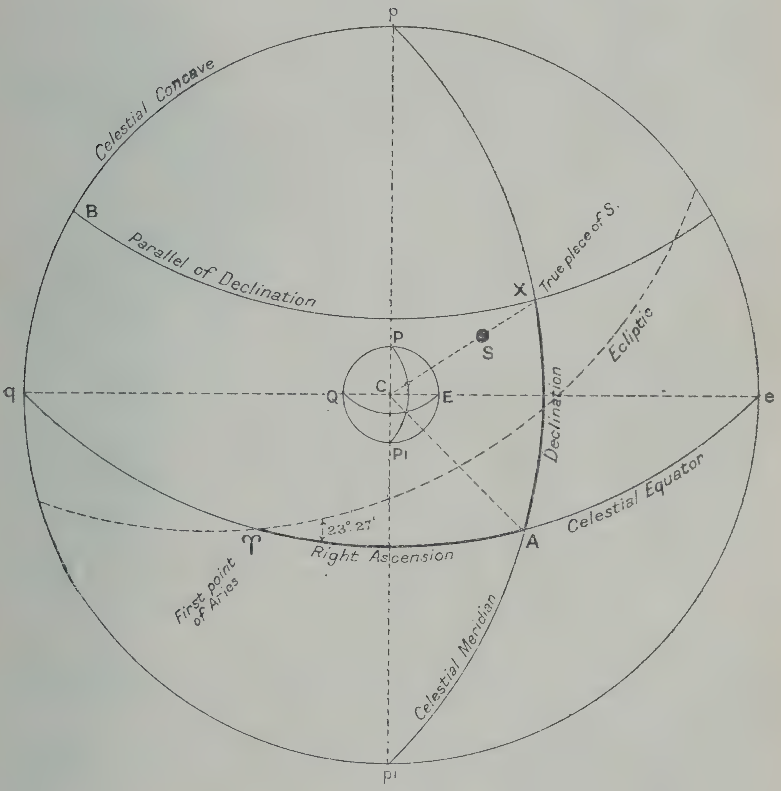


Fig. 65.

The true place of a heavenly body is the point where the line joining the centre of the earth to the centre of the body meets the celestial concave. In Fig. 65 *X* is the true place of the body *S*.

Celestial meridians are semi-great circles which join the celestial poles, PXP', Fig. 65, and they correspond to terrestrial meridians.

Parallels of declination are small circles whose planes are parallel to that of the celestial equator BX in Fig. 65, and they correspond to terrestrial parallels of latitude.

The declination of a heavenly body is the arc of the celestial meridian, which passes through the true place of the body, intercepted between the celestial equator and the true place of the body, or it is the angle at the centre of the earth subtended by this arc; it is measured from the celestial equator from 0° to 90°, and is named North or South according as the body is North or South of the celestial equator. Declination on the celestial concave corresponds to latitude on the earth. In Fig. 65, AX or ACX is the declination of the body S.

The polar distance of a heavenly body is the arc of the celestial meridian, which passes through the true place of the body, intercepted between the elevated pole and the true place of the body, and is, therefore, $90° \pm$ declination. In Fig. 65 PX is the polar distance of the body S to an observer in North latitude, and $P'X$ to an observer in South latitude.

The right ascension (R.A.) of a heavenly body is the arc of the celestial equator intercepted between the first point of Aries and the celestial meridian which passes through the true place of the body; it is measured Eastward from the first point of Aries, increasing from 0° to 360° (or 24 hours). In Fig. 65 ♈A is the right ascension of the body S. Right ascension on the celestial concave corresponds to longitude on the earth.

79. Variation in right ascension and declination.—In the case of the sun it will be seen from Fig. 64 that its right ascension on March 21st is 0° (or 0 hours); on June 22nd, 90° (or 6 hours); on September 23rd, 180° (or 12 hours); and on December 22nd it is 270° (or 18 hours). Since the planes of the ecliptic and celestial equator are inclined at an angle of about 23° 27′, it follows that the sun's declination on March 21st is 0°; on June 22nd, 23° 27′ N.; on September 23rd, 0°; and on December 22nd, 23° 27′ S.

In a similar way it may be shown that there are considerable periodic changes in the right ascensions and the declinations of the moon and planets.

The stars are so distant that their positions are unaffected by the annual change of position of the earth, and their declinations and right ascensions only change by a small yearly amount, dependent principally on the slight annual movement of the first point of Aries.

The right ascensions and declinations of the centres of heavenly bodies are obtained by the fixed instruments of astronomical observatories, and are tabulated in the Nautical Almanac for each year.

In this book the general abbreviation for the right ascension of a heavenly body is R.A.✱.

CHAPTER X.

THE GREENWICH DATE AND CORRECTION OF RIGHT ASCENSION AND DECLINATION.

80. The year and the month.—It has just been shown how the positions of heavenly bodies are referred to the celestial concave by means of their right ascensions and declinations. As the right ascensions and declinations are continually changing, we have to show how to find these elements at any instant of time, from the particular values tabulated in the Nautical Almanac; in other words, we have to find the right-ascension and declination at a particular date. Now the date, at which an observation is taken, is the interval of time that has elapsed since some particular event; this interval is measured in various units of time which depend on the intervals occupied by the earth in its revolution round the sun and its rotation on its axis.

The largest unit is the mean solar year, which is the interval between two successive passages of the sun through the first point of Aries.

The next unit in order of magnitude is the calendar month. A lunar month is the interval occupied by the moon in revolving round the earth with reference to the sun; as the mean solar year contains about twelve lunar months, but not an exact number, it has been found convenient to divide the mean solar year into a series of twelve periods, each having a fixed number of days: these periods are the calendar months now in use.

In order to explain the smaller units of time we must first explain how the rotation of the earth on its axis is made use of to measure them.

81. Celestial meridians of observer and heavenly body.—The earth rotates on its axis from West to East; consequently the heavenly bodies appear to us to revolve round the earth from East to West. For this reason we regard the earth as fixed and the heavenly bodies as rotating round the earth together with the celestial concave, so that the plane of each celestial meridian coincides in turn with the plane of the meridian of the observer.

That particular celestial meridian whose plane coincides with that of the meridian of the observer at any instant, is called the celestial meridian of the observer at that instant.

The celestial meridian of a heavenly body is that celestial meridian which passes through the true place of the body.

82. The day.—When the celestial meridian of a heavenly body and the celestial meridian of an observer coincide, the body is said to be on the observer's meridian, to pass the observer's meridian, or to be in transit, and the interval between two successive meridian passages of a body is used as a means of measuring time; this interval is called a day. There are different kinds of days, which take their names from the different bodies to whose meridian passages they refer.

83. The solar day.—The solar day is the interval of time between two successive passages of the sun's centre over the same meridian. The solar day begins when the sun's centre is on the meridian of the observer, and at this instant it is said to be apparent noon at his meridian. Observations show that this interval is not the same for any two days in succession. This is due to two causes :—

(*a*) The sun does not move in the celestial equator, but in the ecliptic.

(*b*) The sun's motion in the ecliptic is not uniform, the velocity of the earth in its orbit varying with its distance from the sun.

The length of the solar day is, therefore, variable, and clocks cannot be regulated to measure it.

84. The mean solar day and mean solar time.—In order to obtain a uniform measure of time, an imaginary day is employed, called a mean solar day, which is equal in length to the mean or average of all the solar days in a mean solar year. There are 365·242216 mean solar days in a mean solar year.

The mean solar day refers to the meridian passage of an imaginary sun, called the mean sun, which is conceived to move in the celestial equator with the true sun's mean rate of motion in right ascension. The mean sun is regulated with regard to the true sun by means of a fictitious body, which is conceived to move in the ecliptic with the average speed of the true sun, and to coincide with the sun when the earth is nearest to the sun.

When this fictitious body passes the first point of Aries, the mean sun is supposed to start from that point and to move in the celestial equator with the same uniform speed as the fictitious body in the ecliptic.

A mean solar day at any place is considered to begin when the mean sun is on the meridian of that place (mean noon), and is measured by the interval which elapses between two successive passages of the mean sun over that meridian. This interval is divided into 24 mean solar hours, each being again subdivided into minutes and seconds. A clock regulated to keep this time is called a mean solar clock, and the time shown by it is called mean time.

For convenience the civil day begins at midnight and ends at the next midnight, midnight being the instant at which the mean sun is on that meridian the longitude of which differs by 180° from that of the place. It comprises 24 hours, which, however, are counted in two series of 0 hours to 12 hours; the first is marked A.M., extending from midnight to noon, and the second is marked P.M., extending from noon to midnight.

The astronomical day begins at noon on the civil day of the same date. It also comprises 24 hours, but these are reckoned from 0 hours to 24 hours, and extends from noon of one day to noon of the next. It follows that, whereas 2^h P.M., January 9th civil time is January 9th, 2 hours astronomical time; 2^h A.M. January 9th civil time is January 8th, 14 hours astronomical time.

Thus we see that the date at which an observation is taken may be expressed in hours, minutes, and seconds of a particular mean solar day of a particular month of a particular mean solar year; and that the mean solar day may be civil or astronomical.

The mean solar time at any place is denoted by M.T.P. (mean time at place) and on board a ship by S.M.T. (ship mean time).

The time kept by clocks in England is the mean solar time at Greenwich, and is denoted by G.M.T. Chronometers are carried on board ship and from them the G.M.T. can always be found. To avoid the necessity of moving the chronometers, a watch called a deck or hack watch is used for noting the time at sea, and its error on G.M.T. is found by comparison with the chronometers.

85. Change of time for change of longitude.—With regard to the mean sun *M*, in Fig. 66, 24 mean solar hours will elapse between two successive passages across the same meridian, and, therefore, if we suppose 24 meridians to be drawn at equal distances apart $\left(\frac{360°}{24} = 15°\right)$, they will by the rotation of the earth pass successively under the mean sun at intervals of one mean solar hour.

If one of these 24 meridians be that of Greenwich, *PG* in Fig. 66, the first of those Eastward of that meridian, *PE*, will evidently pass under the mean sun one mean solar hour before, and the first Westward of Greenwich, *PW*, one hour after the mean sun has crossed that meridian. In other words, at Greenwich mean noon, the mean time at every place on the meridian *PE* will be 1^h P.M., and similarly at the same instant the mean time at every place on the meridian *PW* will be 11^h A.M.

From this it follows that time is converted into arc at the rate of 15° to an hour, which is the same as 1° to 4 minutes, or $1'$ to 4 seconds, or $1''$ to $\frac{1}{15}$th of a second of time.

Inman's tables give the Log. Haversines for angles expressed either in arc or time; consequently time may be converted into arc, or *vice versâ*, by inspection of these tables. To avoid the risk of arithmetical mistakes, this method should always be employed. In the event of no tables being available, arc may be converted into time and *vice versâ* by remembering the relations stated above.

It will be seen that at every place on the meridian of Greenwich, *PG* in Fig. 66, the time will be mean noon (G.M. Noon); at every place on the meridian *PE* the M.T.P. is 1^h P.M., and at every place on the meridian *PW* the M.T.P. is 11^h A.M. From this we see that the difference in time at the two meridians, expressed in arc, is the difference of longitude of the two meridians: thus the difference between the M.T.P. of the meridians *PE* and *PW* is 2 hours, which, expressed in arc, is 30°, and this is the *d* Long. between the two meridians. When one of the meridians considered is that of Greenwich, the difference between the longitudes becomes the longitude of the other meridian, and so the longitude of a place expressed in time is the difference between the G.M.T. and the M.T.P. at any instant.

In Fig. 66, the longitude of *PE* is 15° E., and the G.M.T. is 0 hours or 24 hours. The M.T.P. of the meridian *PE* is 1 hour, so that, since the longitude expressed in time is 1 hour, we see that

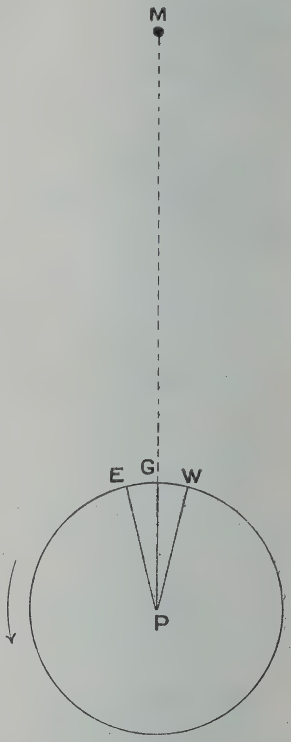


FIG. 66.

$$\text{M.T.P.} = \text{G.M.T.} + \text{Long. of } PE.$$

Similarly with regard to the meridian *PW*,

$$\text{M.T.P.} = \text{G.M.T.} - \text{Long. of } PW.$$

Thus, when finding the S.M.T. or M.T.P., we add or subtract the longitude of the ship or place, expressed in time, to the G.M.T. or from it, according as the place is in East or West longitude. This is easily remembered by aid of the following rhyme:—

Longitude East, Greenwich time least;
Longitude West, Greenwich time best.

86. The Greenwich date.—All the elements tabulated in the Nautical Almanac are given for various hours of Greenwich mean time, some being given for G.M. Noon only and some for every two hours. In order to take out the elements for any date it is necessary to find the G.M.T. corresponding to that date, and to find this we apply to the time shown by the chronometer, or deck watch, the error of the instrument on G.M.T.

The G.M.T. is always expressed in astronomical time and, since the dials of most chronometers and watches are marked from 0 to 12 hours, it may sometimes be necessary to add 12 hours to the chronometer or watch time, and to put the day of the month one day back. To determine whether this must be done, an approximate G.M.T., called the Greenwich date (G.D.), should always be found by applying the estimated longitude (in time) to the S.M.T. or M.T.P. expressed in astronomical time.

Example 1:—August 3rd, at 5^h 32^m P.M. (S.M.T. nearly) in estimated longitude 150° 30′ W. a chronometer showed 3^h 23^m 15^s, its error on G.M.T. being 10^m 20^s slow. Required the G.M.T.

S.M.T.	5^h	32^m	Aug. 3rd	Chron. - -	3^h	23^m	15^s	
Long.	+10	02	(W.)	Error on G.M.T.	0	10	20	slow
G.D.	15	34	Aug. 3rd		3	33	35	
				Add - -	12	00	00	
				G.M.T. - -	15	33	35	Aug. 3rd

Example 2:—March 10th, at 2^h 10^m A.M. (S.M.T. nearly) in estimated longitude 20° 43′ E., a chronometer showed 0^h 2^m 50^s, its error on G.M.T. being 0^h 45^m 16^s slow. Required the G.M.T.

S.M.T.	14^h	10^m	Mar. 9th	Chron. - -	0^h	02^m	50^s	
Long.	−1	23	(E.)	Error on G.M.T.	0	45	16	slow
G.D.	12	47	Mar. 9th		0	48	06	
				Add - -	12	00	00	
				G.M.T. - -	12	48	06	Mar. 9th

87. Correction of right ascension and declination.—(*a*) *The Sun.*—As will be presently understood, after reading Chapter XI., it is unnecessary to find the right ascension of the sun.

The declination of the sun is given in the Abridged Nautical Almanac on page I. of every month. The name of the declination is indicated by N. or S. prefixed to it at every third noon, and also at each of the two noons between which it changes name. The value of the declination for any G.M.T. other than noon is found as follows:—Take the interval between the G.M.T. and the nearest noon; express it in hours and decimals of an hour. Take the value of the declination and its variation in one hour at that noon. Multiply the variation in one hour by the interval. Apply the product as a correction to the noon value, additive or substractive as indicated by inspection of the Almanac. When a change of name in declination occurs during the interval, it is made evident by the fact that the correction is greater than the noon value and is subtractive.

On pages III. to VI. of every month the value of the declination is given for every even hour of G.M.T., and it may be taken out at sight. In the following examples the multiplication is not shown.

Example 1:—Required the sun's declination at G.M.T. April 12th 1914, 5^{h} 41^{m}. The nearest noon is that of April 12th, and the interval is 5·7 hours. The variation in one hour is 0′·92. By inspection the value required is greater than the noon value.

At April 12th, G.M. Noon, Sun's Dec.	8° 28′·5 N.
Add 5·7 × 0′·92	+ 5·2
At G.M.T. required	8 33·7 N.

From page IV. an estimate, made between the values for four and six hours on April 12th, gives the same result.

Example 2:—Required the sun's declination at G.M.T. March 20th 1914, 19^{h} 53^{m}.

The nearest noon is that of March 21st, and the interval is 4·1 hours. The variation in one hour is 0′·99. By inspection a change of name may occur.

At March 21st, Noon, Sun's Dec.	0° 00′·8 N.
Subtract 4·1 × ·99	− 4·1
At G.M.T. required	0 03·3 S.

The correction is subtractive and exceeds the noon value, so that there is a change of name.

From page V. the same result may be estimated.

(*b*) *The Moon.*—The right ascension and declination of the moon are given on pages VII. to X. for every month for every even hour of G.M.T., and the two hourly differences enable the value for any intermediate G.M.T. to be readily obtained by inspection of the table of proportional parts; this table will be found at the end of the Almanac, the arguments being, at the top of the page, the two hourly differences, and at the left-hand side of the page, the interval from the nearest even hour of G.M.T.

Example:—Required the right ascension and declination of the moon for G.M.T. March 5th 1914, 9^{h} 36^{m}.

The nearest even hour is 10 and the interval is 24 minutes. With 288, the difference between 8 hours and 10 hours, at top of page, and 24 minutes, at left-hand side of page, as arguments, it will be found that 58 seconds should be subtracted from the R.A. for 10 hours. Similarly 0′·6 is found to be the amount to be subtracted from the declination for 10 hours.

At March 5th, 10^h			
R.A. Moon - -	$5^h\ 26^m\ 59^s$	Dec.	28° 29′·5 N.
Proportional parts for 24^m	−58		− 0 ·6
At G.M.T. required -	5 26 01		28 28 ·9 N.

(*c*) *The Planets.*—The right ascensions and declinations of Venus, Mars, Jupiter, and Saturn are given on pages XI. and XII. of every month for G.M. Noon of each day; the values for any other G.M.T. can be found by means of the table of proportional parts, using as arguments the difference in 24 hours at the top of the page and the interval from the nearest G.M. Noon at the right-hand side of the page.

(*d*) *The Stars.*—The right ascensions and declinations are given of all stars, of magnitudes 3 and upwards, at intervals of 90 days; the approximate values for any day can be taken out by inspection.

88. Adjusting ship's clocks for change of longitude.—It is convenient for many reasons to keep the ship's clocks adjusted so as to show S.M.T. as nearly as possible.

Suppose a ship starts from the meridian of Greenwich with her clocks showing G.M.T. On arriving at the meridian of 15° E. she will have changed her longitude (expressed in time) by 1 hour, so that the time at this meridian is 1 hour in advance of G.M.T.; consequently, when a ship steams East it is necessary, in order to keep her clocks adjusted to S.M.T., to put them on by an amount equal to the *d* Long. expressed in time. Similarly, when steaming West, it is necessary to put the clocks back.

It is customary to adjust the clocks of a man-of-war during the night, or in the morning watch, so as to interfere with the work of the ship as little as possible, and to adjust them so that they will show correct time at the following noon. It may be convenient, when a ship is on a long voyage, to adjust the clocks so that they will show XII. at the next apparent noon, in order that observations of the sun, when on the meridian, can be made at noon by the ship's clocks.

Let us again consider the change of time on board the ship which is steaming East. When in longitude 180° E. the S.M.T. will be 12 hours in advance of the G.M.T. at any instant, and this introduces an important complication.

Suppose the ship to be in longitude 179° 45′ E. ($11^h\ 59^m$ E.) at 2^h P.M. on January 4th, and that her longitude after an interval of one hour is 179° 45′ W. (11^{h} 59^{m} W.). Now the G.M.T. at 2^{h} P.M. is given by

S.M.T. - - - 2^{h} 00^{m} January 4th.
Long. - - - 11 59 (E.)
G.M.T. - - - 14 01 January 3rd.

One hour later her G.M.T. is 15^{h} 01^{m} January 3rd, and her S.M.T. at the same instant is given by

G.M.T. - - - 15^{h} 01^{m} January 3rd.
Long. - - - 11 59 (W.)
S.M.T. - - - 3 02 January 3rd.

Therefore the S.M.T. has changed in one hour from 2^{h} P.M. January 4th to 3^{h} 02^{m} P.M. January 3rd. From this we see that when crossing the meridian of 180° from East longitude to West longitude, the date will alter one day back. Similarly it may be shown that when crossing the meridian of 180° from West longitude to East longitude the date will advance one day.

When navigating in the vicinity of the meridian of 180°, the possibility of using a Greenwich date with an incorrect day of the month may be avoided by noting that the sequence of the days of the month used in the Greenwich date, from day to day, remains unbroken.

89. Standard times.—If every place in the same country kept the time appropriate to its meridian—that is, M.T.P.—difficulties would arise in the transactions of ordinary life, in particular as regards railways. For this reason a system of standard times has been adopted, by which all places in one particular country, or division of a country where it is a large one, keep the same time—which is that of some important place or meridian; in the latter case the time is generally regulated by Greenwich mean time, and is a certain number of hours in advance, or behind it, depending on the average longitude of the country. In England, Scotland, and Wales, G.M.T. is kept in all ports, and this time is also kept in all the ports of France, Belgium, Spain, and Portugal.

The time at the meridian of 15° E. is one hour in advance of G.M.T.; this time is called Mid-European time and is kept by Germany, Austria, Denmark, Sweden, Norway, Italy, Malta, and other countries which are situated in about the same longitude.

East European time is two hours in advance of G.M.T. It is the time for the meridian of 30° E., and is kept by Egypt, South Africa, and Asia Minor.

Similarly other times, which are a certain number of hours in advance or behind that of Greenwich, are kept in other parts of the world; for example, New Zealand's standard time is 11 hours 30 minutes fast on G.M.T.

A few countries keep the M.T.P. of a particular place: for example, Ireland's standard time is that of the meridian of Dublin, which is 25 minutes 21·1 seconds slow on G.M.T.

The standard times kept in any particular country are given in the sailing directions, in a table towards the end of the unabridged edition of the Nautical Almanac, and in the Admiralty List of Lights and Time Signals.

When, therefore, a ship steams from one port to another, at both of which the same standard time is kept, it is generally unnecessary to alter the ship's clocks during the voyage.

The meridian of 180° passes through several groups of islands, so that it is possible for the dates at two islands in any particular group to differ. To avoid the inconvenience arising from a difference of date in adjacent islands, the meridian of 180°, in the vicinity of each group, is broken and replaced by a zig-zag line which leaves the whole group to one or other side of it. This line is called the date or calendar line, and countries, situated on opposite sides of it, keep different dates. Information relating to the date line will be found in the Admiralty List of Lights and Time Signals.

When proceeding to a place, which does not keep the date corresponding to its longitude due to the position of the date line, care must be taken when working observations to use the correct G.D. The possibility of error may be avoided by noting that the sequence of the days of the month used in the Greenwich date, from day to day, remains unbroken; after the meridian of 180° has been crossed, the Greenwich date may be found by remembering that, if the date has not been changed on crossing the meridian of 180°, the name of the longitude must not be changed.

Example.—Suppose a ship to leave a New Zealand port, the longitude of which is 175° E. on January 3rd, on a voyage to the Friendly Islands, (Long. 175° W.). On this voyage the ship will not cross the date line, because in this vicinity the date line coincides with the meridian of 172° 30′ W.; therefore it is not desirable to change the date. On January 7th, at about 7^h A.M., in estimated longitude 177° W., an observation for finding the position of the ship was taken. The G.D. of the observation is found as follows:—

M.T.P. (according to date used in ship)	$19^h\ 00^m$ January 6th.
Long. (183° E.) - - - - - -	12 12 (E.)
G.D. - - - - - - - -	6 48 January 6th.

CHAPTER XI.

THE ZENITH DISTANCE AND AZIMUTH AT THE ESTIMATED POSITION.

---

90. Connection between a position on the earth and a heavenly body.—Having shown how a position of a heavenly body on the celestial concave may be found at any instant, we have now to find how the body is situated with regard to the estimated position of the ship, and to do this we have to bring the estimated position into relation with the true place of the body by referring the estimated position to the celestial concave.

The zenith of a position on the earth's surface is the point where the normal to the earth's surface at the position intersects the celestial concave, Z in Fig. 67. The celestial meridian which passes through the zenith is in the same plane as the meridian of the position on the earth's surface.

Great circles of the celestial concave which pass through the zenith are called circles of altitude.

The connection between a position on the earth and a heavenly body, which we require to find, is the connection between the two points Z and X on the celestial concave, X being the true place of the heavenly body.

In Fig. 67, P is the celestial pole, Z the zenith of the estimated position E, and X the true place of the body S. The spherical triangle PZX formed by the celestial meridian of the estimated position (PZ), the celestial meridian of the heavenly body (PX) and the circle of altitude (ZX) is called the astronomical or position triangle. The connection between Z and X is known if we can determine the angle PZX and the side ZX; in other words, the bearing and distance of X from Z.

91. The azimuth.—The azimuth of a heavenly body, at any instant at any place, is the angle at the zenith of that place between the celestial meridian of the place and the circle of altitude which passes through the true place of the body at that instant. It is measured from that part of the meridian which is on the polar side of the zenith towards East or West from 0 to 180°. In Fig. 67 the angle PZX is the azimuth of the body S at the estimated position E.

92. The zenith distance.—The zenith distance (z) of a heavenly body, at any instant at any place, is the arc of a circle of altitude intercepted between the zenith of the place and the true place of the body at that instant. In Fig. 67, ZX is the zenith distance of the body S at the estimated position E.

93. The astronomical triangle.—In order to find the azimuth and zenith distance we must know three elements of the astronomical triangle *PZX*.

The side *PZ* which measures the angle *PCE*, that is 90°—*ECQ*, is the co-latitude of *E*, which is obtained as explained in Chapter VI.

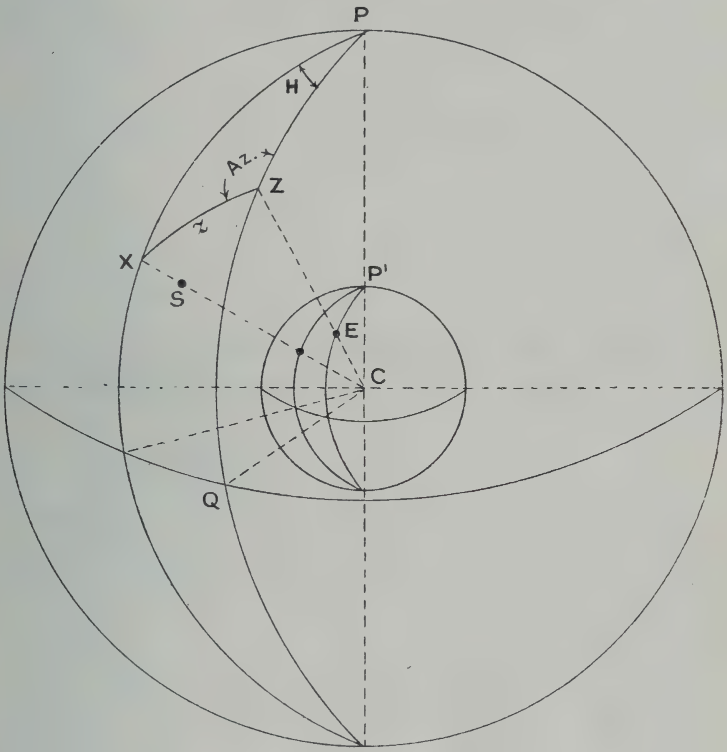


Fig. 67.

The side *PX* is the polar distance of the body *S*, that is 90° ± the declination of the body, and is obtained from the Nautical Almanac.

Therefore, *PZ* and *PX* being known, if we know the angle *ZPX* three elements of the triangle are known, and any one of the others can be found.

94. The hour angle.—The hour angle (*H*) of a heavenly body, at any instant at any place, is the angle at the celestial pole between the celestial meridian of the place and the celestial meridian of the body at that instant. It is measured from the celestial meridian of the place Westward from 0 to 24 hours. It may also be regarded as the arc of the celestial equator intercepted between the two celestial meridians. In Fig. 67, *ZPX* is the hour angle of the body *S* at the estimated position *E*.

In Fig. 68, let *PZ* be the celestial meridian of the estimated position, PX the celestial meridian of the heavenly body at any instant, and M the position of the mean sun on the celestial equator; then, since the mean sun revolves at a uniform rate, the hour angle of M (ZPM) is the mean solar time at that instant at the estimated position (M.T.P.). Similarly the hour angle of the mean sun at the position of the ship is the mean solar time at the ship (S.M.T.).

The apparent solar time, at any instant at any place, is the hour angle of the sun at that instant at that place (A.T.P. or S.A.T.), ZPX in Fig. 68, X being the true place of the sun.

95. The equation of time.—The equation of time (Eq. T.), at any instant at any place, is the difference between the apparent solar time and the mean solar time at that instant at that place. It is, therefore, the difference between the hour angles of the sun and mean sun; that is, the angle at the pole between the celestial meridians of the sun and mean sun. In Fig. 68, the equation of time is the angle XPM, X being the true place of the sun.

The equation of time is tabulated in the Nautical Almanac for every day of the year. Since the mean sun is sometimes ahead and sometimes behind the sun

$$\text{S.A.T.} = \text{S.M.T.} \pm \text{Eq. T.}$$

or, hour angle of the sun at any place $=$ M.T.P. $\pm$ Eq. T.

96. The right ascension of a meridian (or sidereal time).—When X is the true place of any heavenly body other than the sun, the hour angle is found by reference to the first point of *Aries*.

The right ascension of the meridian (R.A.M.), of any place, is the arc of the celestial equator intercepted between the first point of *Aries* and the celestial meridian of that place, and is measured to the Eastward from the first point of *Aries*. In Fig. 68, ΥQ is the right ascension of the meridian PZ.

Now $ZP\Upsilon$ (or $Q\Upsilon$) is the hour angle of the first point of *Aries* at the place, and is also called the sidereal time at that place. Thus it will be seen that the sidereal time at any place and the right ascension of the meridian of that place are identical.

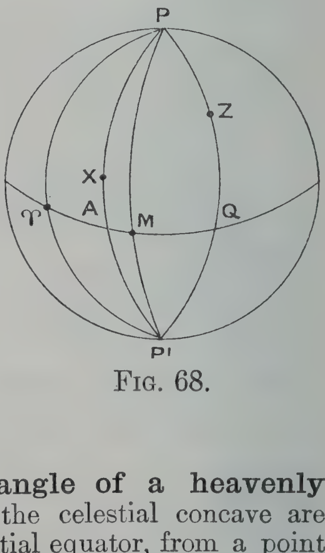


Fig. 68.

97. Formula for the hour angle of a heavenly body.—Suppose that all points of the celestial concave are projected on to the plane of the celestial equator, from a point on the line of the earth's axis which is at an infinite distance beyond the North celestial pole; then in the following figures, ΥQ

represents the celestial equator, PZQ the celestial meridian of the estimated position, and PX the celestial meridian of the body whose true place is X.

In Fig. 69, XPZ or $AQ = \Upsilon Q - \Upsilon A$.

Now XPZ or AQ is the hour angle of the body, ΥQ is the right ascension of the meridian of the estimated position, and ΥA is the right ascension of the body.

Therefore, $H =$ R.A.M. − R.A.✳

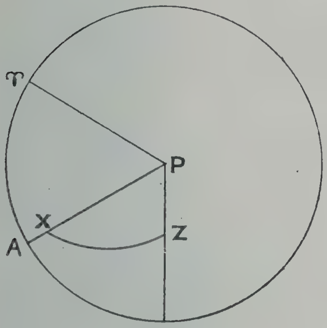


FIG. 69.

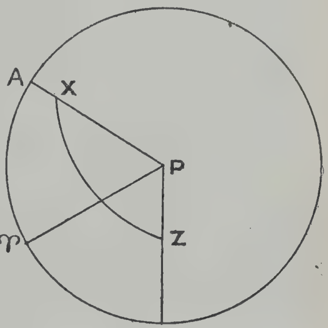


FIG. 70.

In Fig. 70, XPZ or $AQ = \Upsilon Q + A \Upsilon$.

Now $A \Upsilon$ is 24 hours − the right ascension of X.

Therefore, $H = 24^h +$ R.A.M. − R.A.✳

Now the right ascension of a heavenly body may be taken from the Nautical Almanac, so that we have now to find the right ascension of the meridian, and this is done by reference to the mean sun.

In Figs, 71 and 72 let M be the mean sun.

In Fig. 71, $\Upsilon Q = \Upsilon M + MQ$.

Now ΥQ is the right ascension of the meridian (R.A.M.), ΥM is the right ascension of the mean sun (R.A.M.S.), and MQ is the mean time at the estimated position (M.T.P.), and may be found from G.M.T. ± estimated longitude; therefore

R.A.M. = R.A.M.S. + M.T.P.

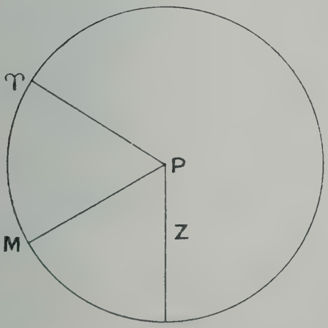


FIG. 71.

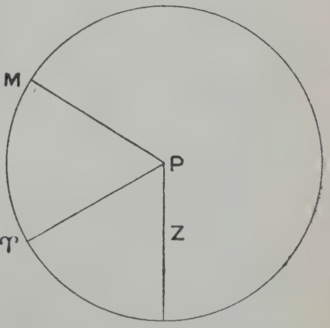


FIG. 72.

$$\begin{aligned}\text{In Fig. 72, } \Upsilon Q &= MQ - M\Upsilon \\ &= \text{M.T.P.} - (24^{h} - \text{R.A.M.S.}) \\ &= \text{M.T.P.} + \text{R.A.M.S.} - 24^{h}.\end{aligned}$$

Combining the formulæ for H and R.A.M. we have

$$H = \text{M.T.P.} + \text{R.A.M.S.} - \text{R.A.}\ast \pm 24^{h} \text{ as necessary.}$$

In the case of the sun, R.A.M.S. − R.A. is the angle at the pole, between the celestial meridians of the mean sun and the sun, and is therefore the equation of time; and the formula for H becomes

$$H = \text{M.T.P.} \pm \text{Eq.T.}$$

The right ascension of the mean sun is tabulated in the Nautical Almanac for every day of the year.

98. Correction of the equation of time.—The equation of time is given in the Nautical Almanac, on page 1 of every month, for G.M. noon; its sense is indicated at the head of the column by precepts, "Add to apparent time" or "Subtract from apparent time," which must be understood also to imply respectively subtract from mean time or add to mean time. When a change of precept occurs in the course of a month, the heading $\dfrac{\text{add to}}{\text{subtract from}}$ and the black line between two noon values indicates that the change occurs at some time between the two noons. The value of the equation of time at any G.M.T., other than noon, is found in a similar way to the declination (§ 87a).

When a change of precept in the equation of time occurs during the interval, it is made evident by the fact that the correction is greater than the noon value and is subtractive.

On pages III. to VI. of every month the value of the equation of time is given for every even hour of G.M.T., and its value for any G.M.T. can be taken out at sight. The note at the bottom of the page denotes how the sign, placed against the equation of time, is to be interpreted.

Example 1:—Required the equation of time for G.M.T. March 20th 1914 19^{h} 53^{m}.

The nearest noon is that of March 21st, the interval is 4·1 hours. The variation in 1 hour is ·75 second.

By inspection the correction is additive.

At March 21st Noon, Equation of time	7^{m} $29^{s}\cdot3$ − to A.T.
Add $4\cdot1 \times \cdot75^{s}$ - - - -	$+3\cdot1$
At G.M.T. required - - - -	7 32·4 − to A.T.

From page V. the same result may be estimated.

Example 2:—Required the equation of time for G.M.T. April 15th 1914 15^{h} 25^{m}.

The nearest noon is April 16th. The interval is 8·6 hours. The variation in 1 hour is ·61 second. By inspection a change of name may occur.

At April 16th Noon Equation of time -	$0^m\ 02^s{\cdot}7$ – to A.T.
Subtract $8{\cdot}6 \times {\cdot}61^s$ - - - -	– 5·2
At G.M.T. required - - - -	0 02·5 + to A.T.

From page IV. the same result may be estimated.

99. Change in the right ascension of the mean sun.—In a mean solar year the mean sun travels through 360°, or 24 hours of right ascension, along the celestial equator. Therefore, since there are 365·242216 mean solar days in a mean solar year, the mean sun moves through $\frac{24}{365{\cdot}242216}$ hours of right ascension in one mean solar day; that is, through 0 hrs. 3 mins. 56·6 secs., which is the change in the right ascension of the mean sun in a mean solar day. In the Nautical Almanac the last column of page I. of every month gives the change in the R.A.M.S. for various intervals of mean solar time up to 24 hours.

100. Correction of the right ascension of the mean sun.—The right ascension of the mean sun is given on page I. of every month for G.M. noon. On pages III. to VI. of every month the R.A.M.S. is given for every even hour of G.M.T.; its value for any other G.M.T. is found by adding, to the value for the preceding even hour, the correction for the remaining interval, from the auxiliary table on page I. of each month headed "Add for hours."

Example 1 :—Required the R.A.M.S. for G.M.T. March 6th 1914, $10^h\ 42^m$.

At March 6th G.M.T. 10^h R.A.M.S. -	$22^h\ 55^m\ 08^s{\cdot}4$
Add for 40 minutes - - - -	6·6
Add for 2 minutes - - - -	·3
At G.M.T. required - - - -	22 55 15·3

Example 2 :—Required the R.A.M.S. for G.M.T. March 22nd 1914, $21^h\ 36^m$.

At March 22nd G.M.T. 20^h R.A.M.S. -	$23^h\ 59^m\ 51^s{\cdot}8$
Add for 1 hour - - - - -	9·9
Add for 30 minutes - - - -	4·9
Add for 6 minutes - - - -	1·0
	24 00 07·6
Subtract - - - - - - -	24 00 00
At G.M.T. required - - - -	00 00 07·6

101. Calculation of the zenith distance and azimuth at the estimated position.—In the astronomical triangle PZX, Fig. 67, we know PZ, the co-latitude of the estimated position, PX, the polar distance of the body, and ZPX, the hour angle of the body at the estimated position. The zenith distance ZX may be found from the formula :—

$$\text{hav } ZX = \text{hav}\,(PX \sim PZ) + \text{hav } \theta,$$

$$\text{where hav } \theta \quad = \sin PZ \sin PX \text{ hav } ZPX.$$

If the latitude (L) and the declination (D) are of the same name, $PZ = 90° - L$ and $PX = 90° - D$ and the formulæ become :—

$$\text{hav } z = \text{hav } (L \sim D) + \text{hav } \theta,$$

$$\text{where hav } \theta = \cos L \cos D \text{ hav } H.$$

If the latitude and declination are of different names, $PZ = 90° - L$ and $PX = 90° + D$ and the formulæ become :—

$$\text{hav } z = \text{hav } (L + D) + \text{hav } \theta,$$

$$\text{where hav } \theta = \cos L \ \cos D \text{ hav } H.$$

Thus we have

$$\text{hav } z = \text{hav } (L \overset{\sim}{+} D) + \text{hav } \theta,$$

$$\text{where hav } \theta = \cos L \cos D \text{ hav } H,$$

the sign ~ or + being used according as L and D are of the same or different names.

Having found the zenith distance ZX, the angle PZX, which is the azimuth, may be found from the formula :—

$$\text{hav } PZX = \text{cosec } PZ \text{ cosec } ZX \sqrt{\text{hav } (PX + ZX - PZ) \text{ hav } (PX - ZX + PZ)}.$$

The following examples show the method of calculating the zenith distance and azimuth :—

Example 1 :—On March 30th 1914 at about $6^h\ 20^m$ P.M. (S.M.T. nearly) in estimated position Lat. 21° 10′ N., Long. 158° 15′ W., a deck watch showed $2^h\ 54^m\ 33^s$ and was slow on G.M.T. $2^h\ 03^m\ 25^s$. Required the zenith distance and azimuth of Venus at the estimated position.

		Dec.	R.A. Venus.
S.M.T.	$6^h\ 20^m$ Mar. 30th	7° 37′·8 N.	$1^h\ 21^m\ 37^s$
Long.	10 33 (W.)	8·6	1 23
G.D.	16 53 Mar. 30th	7 29 ·2 N.	1 20 14

D.W.	2^h	54^m	33^s		
Slow	2	03	25		
	4	57	58		
Add	12	00	00		
G.M.T.	16	57	58 Mar. 30th.		
Long.	10	33	00 (W.)		
M.T.P.	6	24	58		
R.A.M.S.	0	30	54·3 +		
R.A.M.	6	55	52·3		
R.A.✱	1	20	14 —		
H.	5	35	38·3	*L* hav	9·65025
Lat.	21°	10′	N.	*L* cos	9·96966
Dec.	7	29·2	N.	*L* cos	9·99629
(*L* — *D*)	13	40·8		*L* hav *θ*	9·61620

	R.A.M.S.		
	0^h	30^m	$44^s·8$
Add for 50m			8·2
,, ,, 8m			1·3
	0	30	54·3

Nat hav *θ*	·41325
Nat hav (*L* — *D*)	·01418
Nat hav *ZX*	·42743
ZX =	81° 39′·2

ZX - -	81°	39′·2	*L* cosec	10·00463
PZ - -	68	50	*L* cosec	10·03034
ZX — *PZ* -	12	49·2		
PX - -	82	30·8		
PX + *ZX* — *PZ*	95	20	½*L* hav	4·86878
PX — *ZX* + *PZ*	69	41·6	½*L* hav	4·75692
			L hav *PZX*	9·66067
			PZX =	85° 09′

Since the hour angle is less than 12 hours, Venus is West of the meridian; therefore the azimuth is N. 85° 09′ W.

Therefore, at the estimated position, the zenith distance of Venus is 81° 39′·2, and the azimuth N. 85° 09′ W.

Example 2:—On March 4th 1914 at about 8^h 20^m A.M. (S.M.T. nearly), in estimated position Lat. 34° 31′ N., Long. 127° 15′ E. a deck watch showed 9^h 57^m 53^s and was slow on G.M.T. 1^h 54^m 31^s. Required the zenith distance and azimuth of the sun.

		Dec.	Eq. T. + to A.T.
S.M.T. - -	$20^h\ 20^m$ Mar. 3rd.	6° 50′·6 S.	$12^m\ 08^s·3$
Long. - -	8 29 (E.)		
G.D. - -	11 51 Mar. 3rd.		

D.W.	9^h	57^m	53^s		
Slow	1	54	31		
G.M.T.	11	52	24		
Long.	8	29	00 (E.)		
M.T.P.	20	21	24		
Eq. T.	—	12	08·3		
H.	20	09	15·7	*L* hav	9·36680

Dec.	6° 50′·6 S.	*L* cos	9·91591
Lat.	34 31 N.	*L* cos	9·99690
(*L* + *D*)	41 21·6	*L* hav *θ*	9·27961

Nat hav *θ*	·19038
Nat hav (*L* + *D*)	·12470
Nat hav *ZX*	·31508
ZX =	68° 17′·7

ZX - -	68° 17′·7	*L* cosec	10·03193
PZ - -	55 29·0	*L* cosec	10·08409
ZX—PZ -	12 48·7		
PX - -	96 50·6		
PX+ZX—PZ	109 39·3	½ *L* hav	4·91244
PZ—ZX+PZ	84 01·9	½ *L* hav	4·82565
		L hav *PZX*	9·85411
		PZX =	115° 25′

Therefore the sun's azimuth is N. 115° 25′ E.

Therefore, at the estimated position, the zenith distance of the sun is 68° 17′·7 and the azimuth N. 115° 25′ E.

102. Azimuth tables and azimuth diagram.—When great accuracy is not required, instead of calculating the azimuth as in the previous examples, it is customary to obtain it by reference to a book of tables or a diagram. Burdwood and Davis's azimuth tables, and Captain Weir's azimuth diagram, are supplied to all H.M. Ships; the diagram has the advantage that the azimuth can be taken off directly and no interpolation is necessary, as is usually the case when using the tables.

Directions for using the tables are given at the beginning of the book and those for the diagram are printed on it.

CHAPTER XII.

THE TRUE ZENITH DISTANCE AND ASTRONOMICAL POSITION LINE.

103. The true zenith distance.—We have shown how to calculate what the zenith distance and azimuth of a heavenly body would have been, had the observer been at the estimated position of the ship; now, if an observer obtains the zenith distance of the body by observation, comparison of these two zenith distances (the calculated and the true) together with the azimuth of the body, will provide sufficient data for drawing a position line on a chart, as will be explained later. We have now to show the connection between the observed altitude of the body above the sea horizon and the corresponding true zenith distance.

In Fig. 73, which is on the plane of a circle of altitude, let O be the observer's eye, Z his zenith, and OH the observer's horizontal plane. Let S be the centre of a heavenly body whose true place is X.

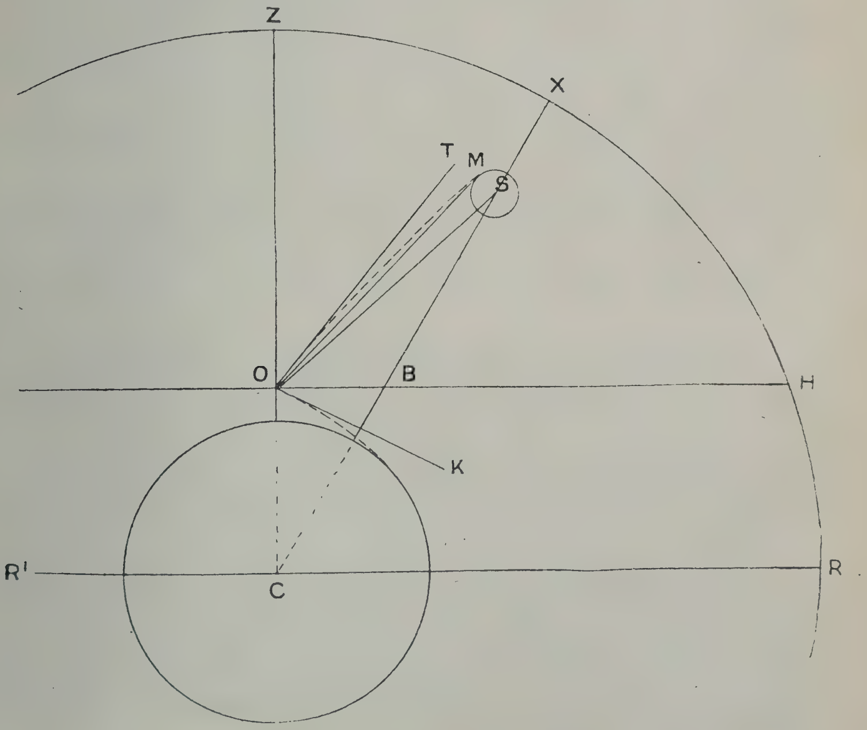


FIG. 73.

The rational horizon is the great circle on the celestial concave whose plane passes through the centre of the earth, and is parallel to the observer's horizontal plane, RR' in Fig. 73.

The true altitude of a heavenly body is the arc of a circle of altitude intercepted between the true place of the body and the rational horizon, XR in Fig. 73; or it is the angle at the centre, XCR.

The observer sees the upper edge M of the body S in the direction OT, due to astronomical refraction, and he sees the sea horizon in the direction OK, due to terrestrial refraction, so that the angle TOK is the observed altitude of the point M.

Now the true zenith distance of the body S is ZX, and this is measured by the angle ZCX, which is the complement of XCR, that is, the complement of the true altitude; therefore to find the true zenith distance we require the true altitude XCR.

$$\begin{aligned}\text{Now } XCR &= XBH\\ &= SOH + OSC\\ &= (MOH - MOS) + OSC\\ &= (TOH - TOM) - MOS + OSC\\ &= (TOK - HOK) - TOM - MOS + OSC.\end{aligned}$$

Now TOK is the observed altitude of the upper edge of the body above the sea horizon, HOK is the dip of the sea horizon, TOM is the astronomical refraction for the ray OM, MOS is called the semi-diameter of the body and OSC is called the parallax in altitude of the body; therefore we have

true zenith distance = 90° − [Obs. altitude − dip − refraction − semi-diameter + parallax in altitude].

Had the lower edge of the body been observed the semi-diameter would have been additive to the observed altitude.

Formulæ for astronomical refraction, semi-diameter, and parallax in altitude will now be given.

104. Formula for astronomical refraction.—Refraction, as explained in § 51, is the bending of a ray of light in passing obliquely through media of different densities. But for the existence of the atmosphere surrounding the earth, a ray of light emanating from a point M of a heavenly body S (Fig. 74) would proceed in a straight line to the eye of an observer O, and he would see it in the direction OM'. The atmosphere, however, causes every ray from S to be deflected from a straight line to a curve, which is concave to the centre of the earth, so that the ray which renders M visible to the observer has really pursued the curved track $MRQPO$. The limit of the atmosphere is shown by the outer circle in Fig. 74, and the observer sees the point M in the direction OT which is a tangent to the curve at O.

On account of the great distance of the body, the straight line from O to M, OM', is parallel to MR, and hence the apparent altitude of a heavenly body is greater than the true altitude by the angle $M'OT$, which is called the astronomical refraction for that apparent altitude.

The rays which proceed from a body in the zenith undergo no refraction, because they enter the layers of the atmosphere perpendicularly. When the body is not in the zenith, the refraction increases as the altitude diminishes, and attains its maximum value of about 34′ when the body is on the horizon.

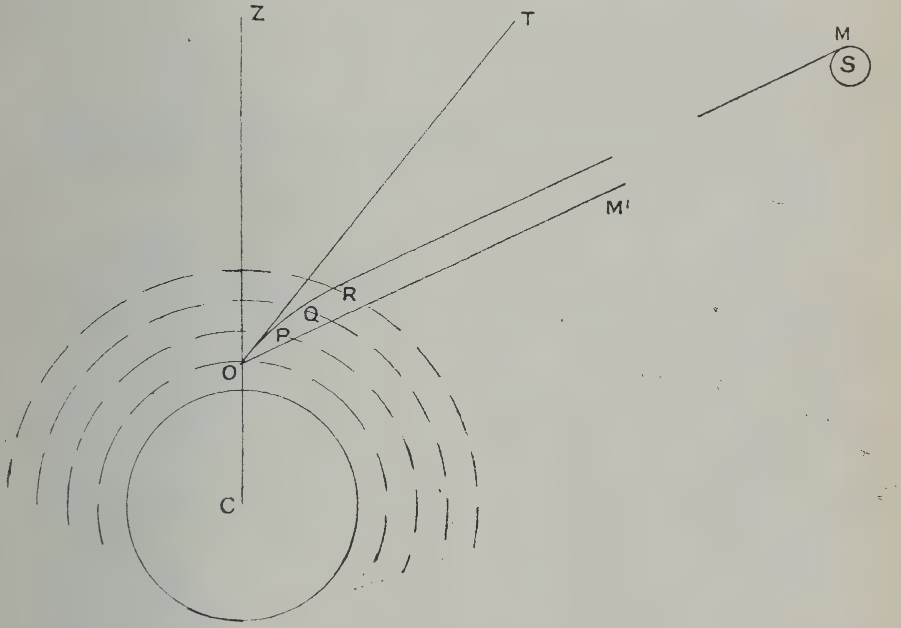


Fig. 74.

The astronomical refraction is found to vary approximately with the cotangent of the altitude, and, for an atmospheric pressure of 30 inches of mercury and a temperature of 50° F., is given by

$$r_0 = 58''{\cdot}36 \cot(\alpha + 4r_0)$$

where α is the apparent altitude of the point observed.

The refraction r_0 is called the mean astronomical refraction and is tabulated in Inman's Tables.

It is assumed that the refraction varies with the density of the air at the earth's surface, so that, if the pressure of the atmosphere is p inches and the temperature $t°$ F., the corresponding refraction r is given by

$$\frac{r}{r_0} = \frac{p}{30}\left(\frac{460 + 50}{460 + t}\right) = \frac{17p}{460 + t}$$

Therefore

$$\frac{r_0 - r}{r_0} = \frac{460 + t - 17p}{460 + t}$$

$$= \frac{250 + t - 10p}{760 + t - 10p}$$ nearly, since p differs very little from 30.

Therefore

$$r_0 - r = \left(\frac{25 + \frac{t}{10} - p}{76 + \frac{t}{10} - p}\right) r_0$$

The value of $r_0 - r$ is tabulated in Inman's Tables under the heading "Correction to Mean Refraction" for various values of $\left(\frac{t}{10} - p\right)$ and a

105. Semi-diameter.—In almost all cases of bodies which do not appear actually as points, such as the stars, it is necessary to observe one or other of their limbs—a term applied to the upper, lower, or any other edge of a circular disc; hence almost every observation of a body having a sensible disc requires the semi-diameter to be either added to or subtracted from it, in order to reduce it to what it would have been if the centre had been observed. When the upper and lower limbs have both been observed, the mean altitude is taken as that of the centre. The upper and lower limbs of a heavenly body are denoted by U.L. and L.L. respectively. An observed altitude of the sun is denoted by the symbol obs. alt. $\overline{\odot}$ or obs. alt. $\underline{\odot}$ according as the U.L. or L.L. has been observed, and the corresponding observed altitudes of the moon are denoted by obs. alt. $\overline{☽}$ or obs. alt. $\underline{☽}$.

For the purposes of navigation telescopes of only weak magnifying power are used in sextants; consequently it is impossible to observe the altitude of a limb of a planet, and therefore only the semi-diameters of the sun and moon require consideration.

The semi-diameters (S.D.) of the sun and moon are tabulated in the Nautical Almanac for G.M. noon of each day; in either case the semi-diameter is the angle subtended at the centre of the earth by a radius of the body. The semi-diameter of the sun requires no correction; that of the moon, however, on account of the moon's rapid change of distance, changes appreciably during the day, and, when required for any G.M.T. other than noon, should be corrected in a similar way to the declination of the sun (§ 87*a*). The moon's semi-diameter requires a further correction as will be explained in § 107.

106. Parallax.—In Fig. 75 the true altitude of the centre of the heavenly body S is SCR, where CR is the rational horizon.

Let S' be the body when it is in the observer's horizontal plane, then $SCR = SBS' = SOS' + OSC$.

Now the angle SOS' = observed altitude − dip − refraction ± S.D. (§ 103).
= apparent altitude corrected for refraction.

The angle OSC is the parallax in altitude of the body S.
The angle $OS'C$ is called the horizontal parallax of the body.
Now in the triangle OCS';

$$\sin CS'O = \frac{CO}{CS'} = \frac{CO}{CS} = \frac{\sin CSO}{\sin COS}$$

$$\therefore \sin CSO = \sin CS'O \times \sin COS.$$

Therefore, since the parallax in altitude and the horizontal parallax are both small angles, we have

Parallax in altitude = horizontal parallax × cos (apparent altitude corrected for refraction).

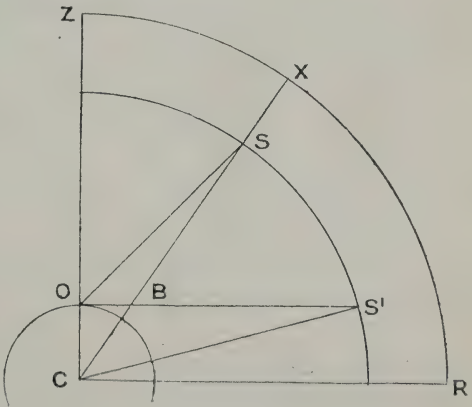


Fig. 75.

The horizontal parallax of a heavenly body depends on the distance of the body from the centre of the earth; for the stars it is extremely minute, and for the sun its mean value is 8″·8. On account of the small distance of the moon from the earth, and the variation in this distance, there is an appreciable daily change in the horizontal parallax of the moon; it is therefore tabulated in the Nautical Almanac for G.M. noon of each day, and when required for any G.M.T., other than noon, should be corrected.

The tabulated values are for an observer situated on the equator, and the horizontal parallax for any other latitude may be found by applying the correction called "Reduction of horizontal parallax for latitude of place" (given in Inman's

Tables), but the correction is so small that it is of no practical importance.

The parallax in altitude is tabulated in Inman's Tables for the sun, moon, and planets.

107. Augmentation of the moon's semi-diameter.—When the moon is above the observer's horizon, as at S in Fig. 76, its distance OS, from an observer at O, is less than its distance OS' when it is in the observer's horizontal plane. Since the horizontal parallax $OS'C$ is small, OS' is nearly equal to CS', and therefore DS' is less than OS' by nearly the earth's radius. Hence, if two observers are situated at O and D, one would see the moon, when at S', in the horizontal plane, and the other observer would see it in the zenith; but, from the observer at O the moon will be more distant than it is from the observer at D by about 4,000 miles, and the diameter would appear to the former about 30″ less than to the latter. It is evident that at any intermediate altitude the distance OS is less than OS', and therefore the moon's diameter at S appears greater than the true or horizontal diameter at S'; therefore the diameter at S is augmented. This increase in the moon's semi-diameter is termed the augmentation.

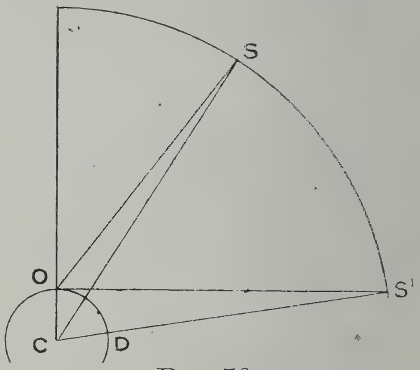


FIG. 76.

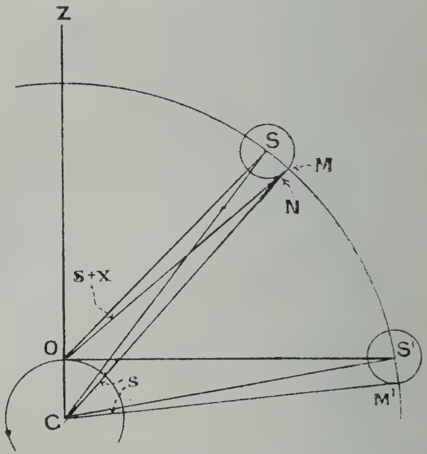


FIG. 77.

In Fig. 77, S is the centre of the moon, whose radius is r; ON and CM are tangents to the moon, from O and C respectively, in the vertical plane of the observer. Let SCM and SON be denoted by s and $(s + x)$ respectively, then x is the augmentation of the moon's semi-diameter. Let the apparent zenith distance of the moon, ZOS, be denoted by $90° - a$, so that a is the apparent altitude, and let the corresponding parallax in altitude OSC be denoted by p, then

$$\sin(s+x) = \frac{r}{OS}$$

$$\sin s = \frac{r}{CS}.$$

Therefore, since s and α are small angles

$$\frac{s+x}{s} = \frac{CS}{OS} = \frac{\sin SOC}{\sin OCS} = \frac{\cos\alpha}{\cos(\alpha+p)}.$$

$$\therefore \frac{x}{s} = \frac{\cos\alpha - \cos(\alpha+p)}{\cos(\alpha+p)}.$$

$$\therefore x = 2s \sin\left(\alpha + \frac{p}{2}\right) \sin\frac{p}{2} \sec(\alpha+p).$$

Let CM' be a tangent to the moon from C when the moon is in the observer's horizontal plane, then

$$\sin OS'C = \frac{R}{CS'}$$

where R is the earth's radius,

and $$\sin s = \frac{r}{CS'}.$$

Therefore

$$\frac{OS'C}{s} = \frac{R}{r} = \frac{11}{3} \text{ nearly.} \quad (\S\ 73.)$$

Now $OS'C$ is the horizontal parallax of the moon and p is the horizontal parallax × $\cos\alpha$, therefore

$$p = \frac{11}{3} s \cos\alpha\,;$$

therefore the augmentation of the moon's semi-diameter is given by

$$x = 2s \sin\left(\alpha + \frac{p}{2}\right) \sin\frac{p}{2} \sec(\alpha+p),$$

where $p = \frac{11}{3} s \cos\alpha$.

The augmentation of the moon's semi-diameter is given in Inman's Tables for various apparent altitudes and semi-diameters.

The great distances of the other heavenly bodies renders any augmentation of their semi-diameters too minute a quantity to be considered.

108. Examples of the correction of altitudes.—

Example 1:—On March 1st, the obs. alt. $\underline{\odot}$ was 20° 18′ 30″; height of eye (H.E.), 50 feet; I.E., $-1'\ 20''$. Required the sun's true altitude.

Obs. Alt. sun's L.L. -	20°	18′	30″
I.E. - -		−1	20
	20	17	10
Dip - -		−6	58
	20	10	12
Refraction		−2	37
	20	07	35
S.D. - -		+16	10
	20	23	45
Parallax -			+8
True Alt. -	20	23	53

For a given height of eye and altitude of the sun, the dip, refraction, and parallax remain the same, while the semi-diameter varies by a small amount during the year from its mean value, 16′. For this reason a total correction in minutes of arc for dip, refraction, parallax, and semi-diameter is tabulated in Inman's Tables with arguments, height of eye, and observed altitude of the L.L. ; a supplementary table gives a small correction for the variation of the semi-diameter. Except when very great accuracy is desired, observed altitudes should be corrected by means of this total correction, which should be applied as shown below.

Obs. Alt. sun's L.L.-	20°	18′	30″
I.E. - -		−1	20
	20	17·2	
Total Corr.		+6·7	
True Alt. -	20	23·9	

When the upper limb of the sun has been observed the same table may be used, but twice the sun's semi-diameter should be subtracted from the result.

Example 2 :—The observed altitude of *Aldebaran* was 18° 20′ 40″ ; height of eye, 50 feet ; I.E., + 1′ 30″. Required the true altitude of Aldebaran :—

Obs. Alt. star - -	18°	20′	40″
I.E. - - -		+1	30
	18	22	10
Dip - - - -		−6	58
	18	15	12
Refraction - -		−2	55
True Alt. - -	18	12	17

A total correction (in minutes of arc) to a star's altitude is tabulated in Inman's Tables, and is applied as follows:—

Obs. Alt. star	18° 20′ 40″
I.E.	+1 30
	18 22·2
Total correction	−9·9
True altitude	18 12·3

As it is never required to work observations of the moon to a very great degree of accuracy, the observed altitude of the moon should always be corrected by means of the total correction.

Example 3:—March 11th 1914, the observed alt. of the moon's U.L. was 35° 13′ 20″; height of eye, 50 feet; I.E., −1′ 10″. Required the true altitude of the moon, the G.D. being 10 hrs.

Horizontal parallax	60′ 56″	Semi-diameter	16′ 38″
Correction	+11	Correction	+3
	61 07		16 41
		Augmentation	+11
			16 52

Obs. Alt. moon's U.L.	35° 13′ 20″
I.E.	−1 10
	35 12·2
Total correction	−8·3
	35 03·9
Semi-diameter	−16·9
	34 47·0
Parallax in alt. for 61′	+50·1
,, ,, ,, ,, 7″	+ ·1
True altitude	35 37·2

109. The geographical position of a heavenly body.—To understand the theory of the position line, as obtained from the observed altitude of a heavenly body and the G.M.T., it is necessary to understand what is meant by the geographical position of a heavenly body.

If a straight line is drawn from the centre of a heavenly body perpendicular to the earth's surface, the point where this line intersects the surface is the geographical position of the body. In Fig. 78, *U* is the geographical position of the body *S*.

We will now show how the latitude and longitude of this point may be found.

(*a*) *To find the latitude*:—

In Fig. 78 let S be the centre of a heavenly body and U the geographical position, and let SU intersect the plane of the earth's equator in K; then the angle UKQ is the latitude of U.

Join C, the centre of the earth, to S. Then

$$UKQ = QCS + CSK.$$

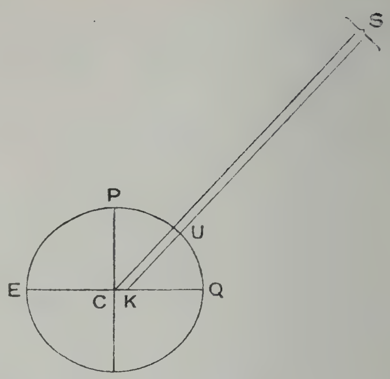


FIG. 78.

On account of the great distances of the heavenly bodies, the angle CSK is inappreciable; therefore, since QCS is the declination of the body (§ 78), we have

Latitude of geographical position = declination of body.

(*b*) *To find the longitude*:—

In Fig. 79, let $P'G$ and PZ be the meridian and the celestial meridian of Greenwich respectively, Z being the zenith of Greenwich. Let PZ' be the celestial meridian of the body S, Z' being the zenith of the geographical position of S, namely U. Let $P'U$ be the meridian of U. Let $P\Upsilon$ be the celestial meridian of the first point of Aries, then

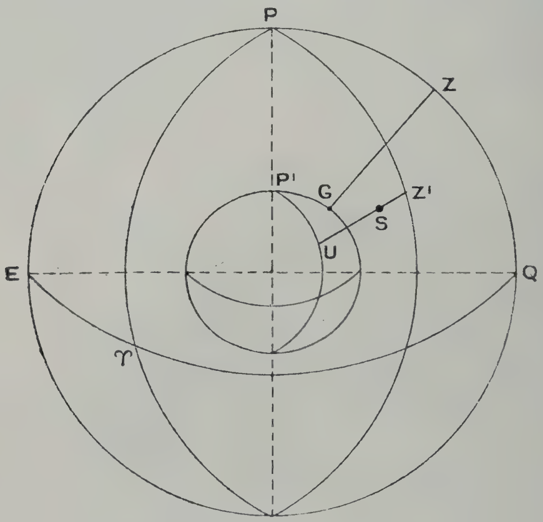


FIG. 79.

$$\begin{aligned}\text{West longitude of } U = GP'U = ZPZ' &= \Upsilon PZ - \Upsilon PZ' \\ &= \text{R.A.M. Greenwich} - \text{R.A.}\ast \\ &= \text{R.A.M.S.} + \text{G.M.T.} - \text{R.A.}\ast\end{aligned}$$

When the body considered is the sun, the difference between R.A.M.S. and the R.A. of the sun is the equation of time, and in this case we have

$$\text{West longitude of } U = \text{G.M.T.} \pm \text{Eq. T.} = \text{G.A.T.}$$

When it is found that the West longitude of U exceeds 12 hours (180°) it must be subtracted from 24 hours (360°), and the result is the East longitude of U.

110. The true bearing of the geographical position.—If we neglect the spheroidal form of the earth, the azimuth of a heavenly body is clearly the same as the angle at the place between the meridian of the place and the great circle which joins the place to the geographical position of the body; in other words, the true bearing of the geographical position of a heavenly body is the same as the azimuth of the heavenly body.

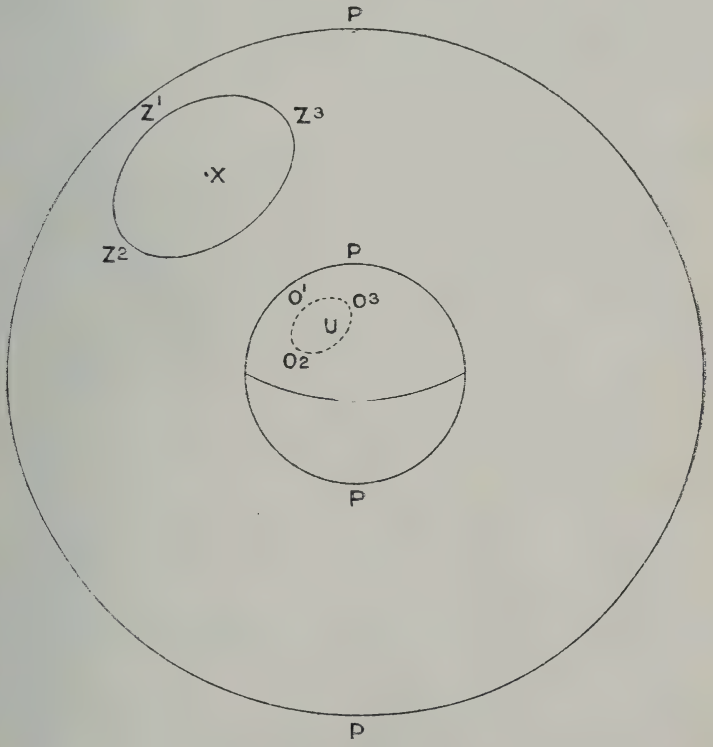


FIG. 80.

111. The circle of position.—In Fig. 80, let X be the true place of a heavenly body and U its geographical position. Let z be the true zenith distance of the body, as obtained from an observed altitude.

Let $Z_1Z_2Z_3$ etc. be a small circle of the celestial concave whose centre is X and whose radius is z; then the observer's zenith must lie somewhere on the circumference of this circle.

Let O_1, O_2, O_3, etc. be the geographical positions of Z_1, Z_2, Z_3, etc. respectively; then the observer is somewhere on a curve $O_1O_2O_3$ etc. of the earth's surface, such that every point of the curve has its zenith on the circle $Z_1Z_2Z_3$ etc. This curve is very nearly a circle, whose centre is the geographical position of the body, and whose radius is the true zenith distance expressed in nautical miles, and it is called a circle of position.

From this we see that the information derived from observations of the altitude of a heavenly body, and the time shown by the deck watch at the same instant, is :—

(*a*) The observer is situated somewhere on the circumference of a circle whose radius is the true zenith distance of the body expressed in nautical miles ; this distance is obtained from the observed altitude.

(*b*) The centre of the circle is the geographical position of the body at the G.M.T. of the observation ; its position is obtained from the time shown by the deck watch and the Nautical Almanac.

A circle of position when represented on the Mercator's chart becomes a curve, and takes one of three forms according as the circle of position lies between the poles, passes through a pole, or encloses a pole.

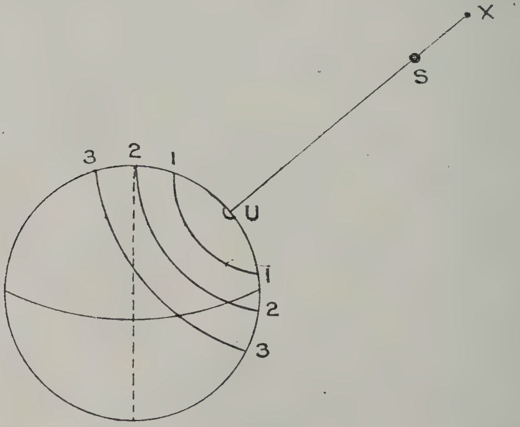


Fig. 81.

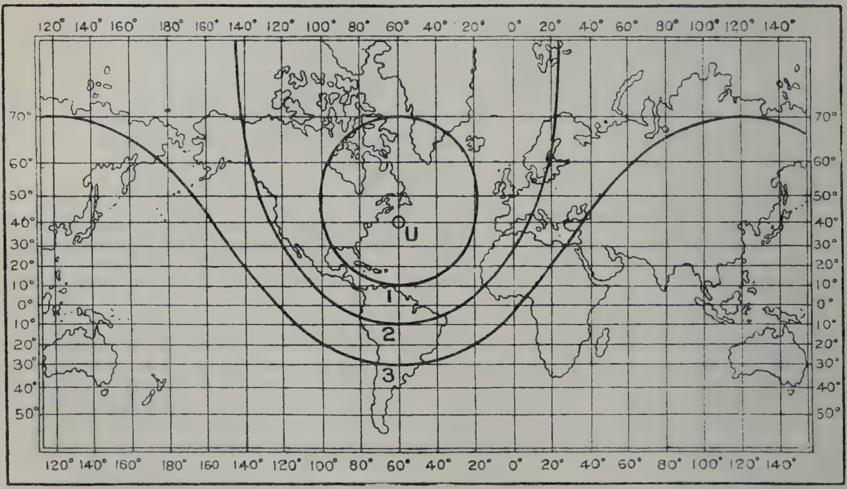


Fig. 82.

In Fig. 82 the curves marked 1, 2, 3 are the representations of the corresponding circles of position marked 1, 2, 3 in Fig. 81.

When the zenith distance is extremely small, the oval type of curve becomes approximately a circle on the Mercator's chart but it should be noted that the centre of this circle is not the geographical position of the body, except in low latitudes.

112. The astronomical position line.—In practice it is only necessary to consider a small portion of the circle of position in the neighbourhood of the estimated position.

In Fig. 83, let E be the estimated position of the ship, and U the geographical position of the heavenly body observed, whose true place is X.

Let the great circle arc EU, produced if necessary, intersect the circle of position JY in J, then EJ is called the intercept.

The small arc of the circle of position which contains J is the position line, and is at right angles to EJ, so that, if we know the magnitude and direction of EJ, the position line is determined with regard to E.

Let Z and Z' be the zeniths of E and J respectively; then, if the earth is assumed to be a sphere, the lines ZE, $Z'J$, and XU intersect at C, the centre of the earth. The error involved in this assumption is extremely minute and of no importance.

We have

$$EJ = EU \sim JU$$
$$= ECU \sim JCU$$
$$= ZX \sim Z'X.$$

Now ZX is the zenith distance of the body at the estimated position at the instant of the observation, as calculated in the manner explained in § 101, and $Z'X$ is the true zenith distance as found from the observed altitude.

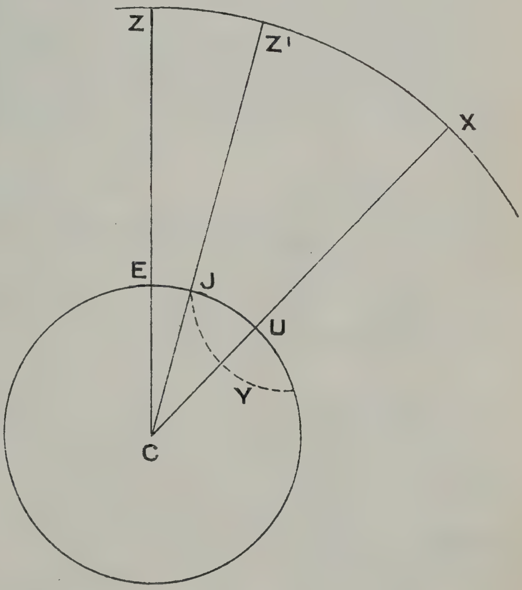


FIG. 83.

∴ Intercept = calculated zenith distance ~ true zenith distance.

Again, the direction of EJ is the same as that of ZX, or in the opposite direction, according as the true zenith distance is less or greater than the calculated zenith distance; in other words, the direction of the intercept, as regards the estimated position E, is the same as the azimuth of the body at the estimated position or in the opposite direction, "towards" or "away," according as the true zenith distance is less or greater than the calculated zenith distance.

Now the intercept is a small arc of a great circle, and is, therefore, practically coincident with the rhumb line drawn through the estimated position in the direction of, or opposite to, the azimuth of the body. The position line, being the small arc of the circle of position in the vicinity of *J*, provided the zenith distance is not very small, may also be regarded as coincident with a rhumb line, and lies at right angles to the azimuth of the body.

Since angles on the earth's surface are correctly represented on the Mercator's chart, it follows that, when the intercept and azimuth have been obtained, the point *J* may be found by laying off, from the estimated position, a course and distance corresponding to the direction and magnitude of the intercept (§ 40). The position line may then be drawn through *J* perpendicular to the intercept *EJ*.

The point *J* may also be found by aid of the traverse table (§ 41).

The following example shows the method of determining a position line from the observed altitude of the sun's lower limb, by plotting, and also by aid of the traverse table :—

Example :—On March 7th, 1914, about 9^h A.M. (S.M.T. nearly), in estimated position Lat. 20° 15′ N., Long. 160° 39′ E., when the deck watch was slow on G.M.T. $2^h\ 17^m\ 27^s$; I.E., +1′ 30″; H.E., 50 ft., the following observation was taken :—

D.W. $8^h\ 02^m\ 36^s$ Obs. Alt. $\underline{\odot}$ 36° 35′ 10″

S.M.T. $21^h\ 00^m$ Mar. 6th. Obs. Alt. $\underline{\odot}$ 36° 35′ 10″ Dec. 5° 42′·7 S.
Long. 10 42 36^s (E.) I.E. +1 30 Eq. T. $11^m 29^s$ + to A.T.

36 36·7
G.D. 10 17 Mar. 6th. Corr. +8·0

36 44·7

D.W. $8^h\ 02^m\ 36^s$ True z 53 15·3
Slow 2 17 27

G.M.T. 10 20 03
Long. 10 42 36 (E)

M.T.P. 21 02 39
Eq. T. −11 29

H. 20 51 10 L. hav 9·20502

Lat. 20° 15′ N. L cos 9·97229
Dec. 5 42·7 S. L cos 9·99784

$(L+D)$ 25 57·7 L hav θ 9·17515

Nat. hav θ ·14968
Nat. hav $(L+D)$ ·05046

Nat. hav z ·20014 Calc. z 53° 09′
True z 53 15·3

Intercept 6·3 away.

From the azimuth tables the sun's azimuth is N. 114° E.

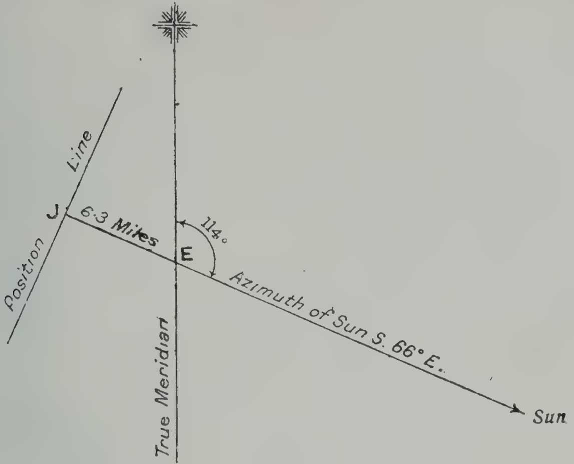


Fig. 84.

Fig. 84 shows the position line obtained from this observation. The point *J*, through which the position line is drawn, may be plotted directly on the chart by laying off a line N. 66° W. (true), 6·3 miles from the estimated position *E*.

The point *J* may also be found by aid of the traverse table as follows:—

Estimated position	Lat.	20° 15′ N.		Long.	160° 39′ E.
N. 66° W. 6′·3	*d* Lat.	2·6 N.	Dep. 5′·8 W.	*d* Long.	6·1 W.
J - -	Lat.	20 17·6 N.		Long.	160 32·9 E.

The position line is now drawn in a direction $\begin{smallmatrix}\text{N.}\\ \text{S.}\end{smallmatrix} 24^\circ \begin{smallmatrix}\text{E.}\\ \text{W.}\end{smallmatrix}$ (true) through the position of *J* thus found.

113. The most probable position from a single observation.—The error of the estimated position is always known within certain limits. If it be assumed that the estimated position is not in error by more than *n* miles, in Fig. 85, let *E* be the estimated position and let a circle with centre *E*, and radius *n* miles, intersect the circle of position at *A* and *B*; then, since the ship's position lies within the circumference of this circle and on the arc *AB*, it must lie between the points *A* and *B*; therefore the best point to assume as the position of the ship is *J*, which is the mean of all the positions which she might occupy, because it is the middle point of *AB*.

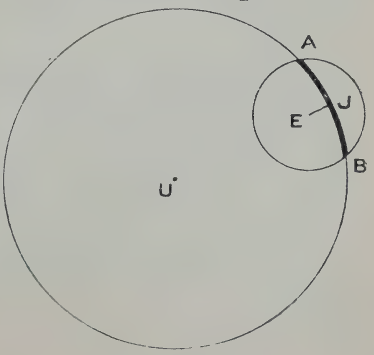


Fig. 85.

114. The value of a single position line.—The information obtained from an observation of a heavenly body is that the ship is situated somewhere on the resulting position line. In the vicinity of land this information is often very valuable, for if the position line, when produced, intersects the land, its direction indicates the course to steer in order to reach the point of intersection; whereas, if it passes clear of land and all dangers, its direction indicates a safe course to steer.

Again, if an observation is taken of a body which is on one beam or the other, the resulting position line indicates whether the ship is on her intended track or to starboard or port of it; and, similarly, if an observation is taken of a body which is either ahead or astern, or nearly so, the resulting position line indicates whether the ship is ahead or astern of her reckoning.

The following examples illustrate the value of a single position line:—

Example 1:—A ship is bound to Plymouth and when in estimated position Lat. 47° 56′ N., Long. 6° 37′ W., it is found from an observation of a heavenly body, whose true bearing is S. 56° E., that the intercept is 7′ towards. The resulting position line *AB*, Fig. 86, is plotted on the chart, and, when produced in the direction N. 34° E. (true), is seen to pass 25 miles off Ushant and 5 miles off the Eddystone to the Eastward. Therefore, wherever the ship may be on the position line, a course to make good N. 34° E. (true) may be steered.

Example 2:—A ship is steaming S. 23° E. (true) and when in estimated position Lat. 50° 43′ N., Long. 6° 23′ W., it is found from an observation of a heavenly body, whose true bearing is S. 80° W., that the intercept is 3′ away. The resulting position line *AB*, Fig. 86, is plotted on the chart, and, when produced in the direction S. 10° E. (true), is seen to pass through the Seven Stones. It is desired to pass between the Seven Stones and the Wolf Rock and at a distance of 6 miles from the former.

Draw a line *CD* parallel to *AB* and at a distance of 6 miles from the Seven Stones. Lay off from *J* a line in the direction S. 23° E. (true), intersecting *CD* in *C*; then *JC* is found to be 27 miles. Therefore, if the ship steers so as to make good S. 23° E. (true), 27 miles, and then alters course so as to make good S. 10° E. (true), her track will then be along the line *CD*.

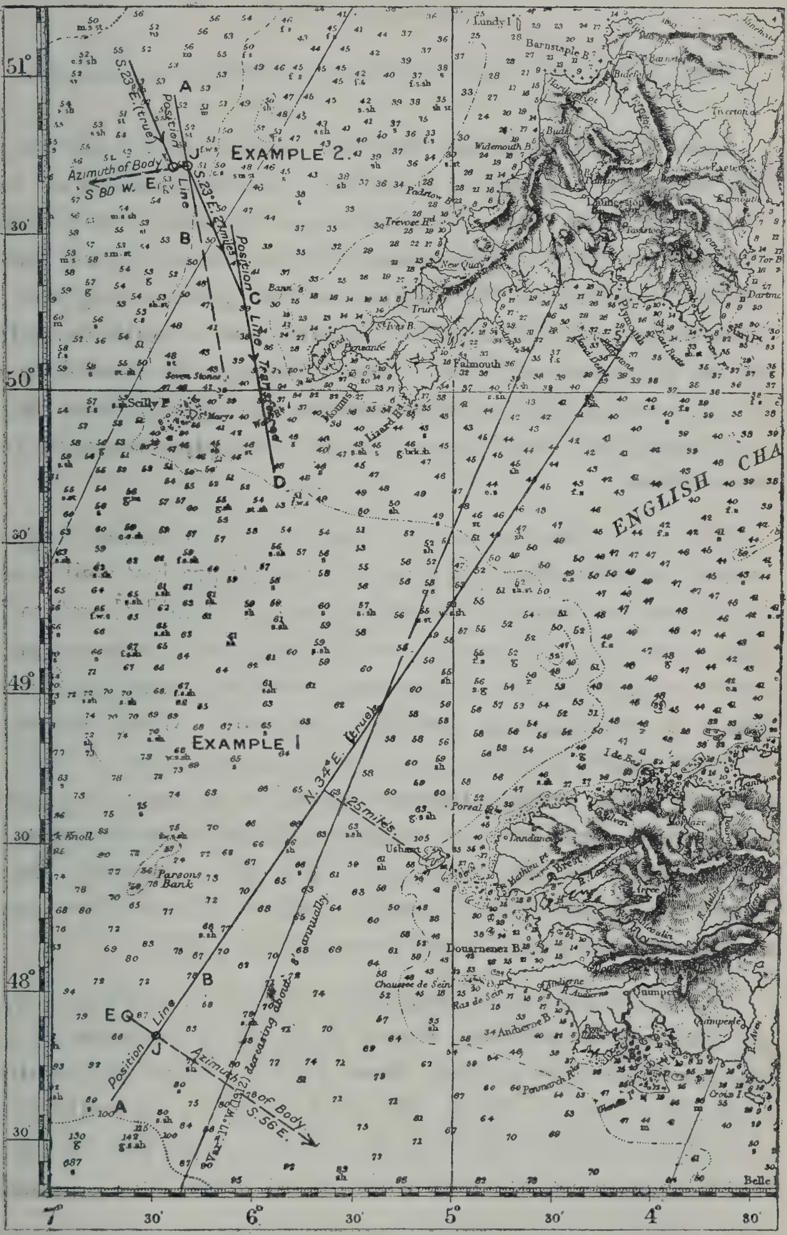

EXAMPLE 2.
A
Position Line
J
Azimuth of Body
S 80 W. E
S.23°E.(true)
S.23°E. 27 miles
B
Position Line Transferred
C
D
EXAMPLE I
N.34°E.(true)
25 miles
Position Line
E
J
A
B
Azimuth of Body S.56°E.
Var. 17°W.(1912) decreasing about 8' annually
ENGLISH CHA
Lundy I.
Barnstaple B.
Widemouth B.
Padstow
Trevose Hd.
New Quay
Truro
St. Ives B.
Lands End
Penzance
Mounts B.
Lizard Hd.
Falmouth
Plymouth
Start Pt.
Dartmouth
Tor B.
Exmouth
Exeter
Tiverton
Launceston
Bude
Hartland Pt.
Seven Stones
Scilly I.
St. Marys
Wolf Rk.
Parsons Bank
Knoll
Ushant
Portsall
I. de Bas
Morlaix
Landerneau
St. Mathieu Pt.
Brest
Douarnenez B.
Chaussee de Sein
Ras de Sein
Audierne B.
Audierne
Quimper
Quimperlé
Penmarch Rks.
Croix I.
Belle I.
51°
30'
50°
30'
49°
30'
48°
30'
7°
30'
6°
30'
5°
30'
4°
30'

Fig. 86.

CHAPTER XIII.

POSITION BY ASTRONOMICAL POSITION LINES.

115. Position from two or more observations.—The position of a ship is found from the intersection of two or more position lines. It is important to obtain the position from two or more simultaneous or nearly simultaneous observations, in order that the accuracy of the position may not be dependent on that of the reckoning, and this is particularly the case in a man-of-war, where there is always the possibility of the ship being engaged in manœuvres or other exercises which may complicate the keeping of the reckoning between two observations.

The best time for taking observations is at morning or evening twilight, when the stars and planets are just visible and the horizon is usually very clearly defined; it should, therefore, be made a rule that, whenever the ship's position is not accurately known, observations of two or more stars or planets should be taken at morning and evening twilight. When selecting heavenly bodies to observe, it should be remembered that the accuracy of the position depends largely on the angle at which the position lines cut one another; this angle is the same as the difference of the azimuths of the bodies, so that bodies should be selected the difference of whose azimuths is as near a right angle as possible, and never less than 30°.

When the intercepts have been found for two observations, the position of the ship, which is at the intersection of the two corresponding position lines, may be found by plotting or by calculation. When the chart is on a sufficiently large scale the method by plotting on the chart has the advantage that the position of the ship with regard to the land is immediately known.

When the chart is on too small a scale, the position lines may be plotted either on the diagram supplied for the purpose or on squared paper. The diagram consists of a mounted sheet on which are drawn meridians and a large compass graduated in degrees. At the side is a scale of differences of meridional parts corresponding to the scale of longitude of the plan.

When finding the position by plotting on squared paper, the relation between departure and difference of longitude should be carefully borne in mind.

116. Examples of finding position by plotting and by calculation.—The method of finding the position by plotting the position lines will be understood from the following examples. In examples (1) and (3) the position lines are plotted on a chart, and in example (1) on squared paper.

It is sometimes convenient to find the position by calculation; in this case the traverse table is employed as shown in examples (2) and (3).

The order in which the work is arranged in the following examples should be carefully noted. It will be seen that there are two distinct arrangements, that shown in example (1) being applicable to simultaneous observations when it is intended to plot the position lines; that shown in examples (2) and (3) being applicable to successive observations, and also to simultaneous observations, when it is intended to find the position by calculation instead of plotting. It is of the utmost importance that observations should be worked out in a systematic manner, because the chance of making mistakes is very much minimised by following set methods.

Example (1):—Position by plotting (*a*) on chart, (*b*) on squared paper. Simultaneous observations.

On April 27th, 1914, at about 7^h 30^m P.M. (S.M.T. nearly) in estimated position Lat. 49° 55′ N., Long. 7° 15′ W., the deck watch was slow on G.M.T. 2^h 29^m 34^s. I.E., + 1′ 30″. H.E., 40 ft.

The following observations were taken to determine the position of the ship:—

Deck watch	5^h 28^m 04^s	Obs. alt. Procyon	37° 28′ 30″
,, ,,	5 29 51	,, ,, Capella	44 51 20

S.M.T.	7^h 30^m	April 27th.
Long.	29	(W.)
G.D.	7 59	April 27th.

	Procyon.			*Capella.*	
Obs. alt.	37° 28′ 30″		Obs. alt.	44° 51′ 20″	
I.E.	+ 1 30		I.E.	+ 1 30	
	37 30·0			44 52·8	
Cor.	− 7·4		Cor.	− 7·2	
	37 22·6			44 45·6	
True *z*	52 37·4		True *z*	45 14·4	
Dec.	5° 26′·7 N.		Dec.	45° 55′ N.	
R.A.	$7^h 34^m 49^s$		R.A.	$5^h 10^m 21^s$	
D.W.	$5^h 28^m 04^s$		D.W.	$5^h 29^m 51^s$	
Slow	2 29 34		Slow	2 29 34	
G.M.T.	7 57 38		G.M.T.	7 59 25	
Long.	29 00 (W.)		Long.	29 00 (W.)	
M.T.P.	7 28 38		M.T.P.	7 30 25	
R.A.M.S.	2 19 29·7 +		R.A.M.S	2 19 29·7 +	
For 1^h	+ 9·9	Cor. for G.M.T.	For 1^h	+ 9·9	Cor. for G.M.T.
„ 50^m	+ 8·2		„ 50^m	+ 8·2	
„ 8^m	+ 1·3		„ 9^m	+ 1·3	
R.A.M.	9 48 17·1		R.A.M.	9 50 14·3	
R.A.	7 34 49		R.A.	5 10 21	
H.	2 13 28·1	*L* hav 8·91602	*H.*	4 39 53·3	*L* hav 9·51688
Lat.	49° 55′ N.	*L* cos 9·80882	Lat.	49° 55′ N.	*L* cos 9·80882
Dec.	5 26·7 N.	*L* cos 9·99803	Dec.	45 55 N.	*L* cos 9·84242
(*L*—*D*)	44 28·3	*L* hav*θ* 8·72287	(*L*—*D*)	4 00	*L* hav*θ* 9·16812
Nat. hav *θ*	·05283		Nat. hav *θ*	·14727	
Nat. hav (*L*—*D*)	·14320		Nat. hav (*L*—*D*)	·00122	
Nat. hav *z*	·19603		Nat. hav *z*	·14849	
Calc. *z*	52° 33′·5		Calc. *z*	45° 19′·8	
True *z*	52 37·4		True *z*	45 14·4	
Intercept	3·9 away.		Intercept	5·4 towards.	
Azimuth from Tables	N. 136° W.		Azimuth from Tables	N. 67° W.	

The position lines are now drawn on the chart as shown in Fig. 87, or on squared paper as shown in Fig. 88.

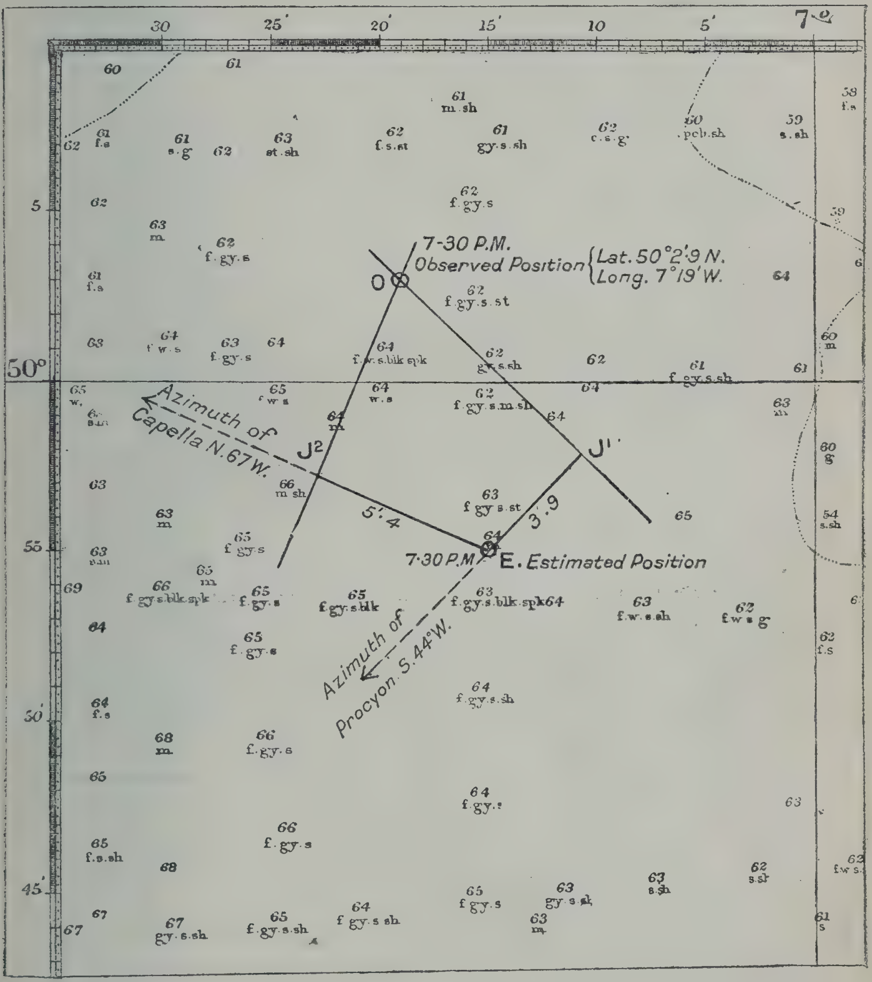

30
25'
20'
15'
10
5'
7°
5
50°
55
50'
45'
7-30 P.M.
Observed Position
Lat. 50°2'9 N.
Long. 7°19' W.
O
J²
J¹
Azimuth of Capella N.67W.
5'.4
3'.9
7·30 P.M.
E. Estimated Position
Azimuth of Procyon S.44°W.

FIG. 87.

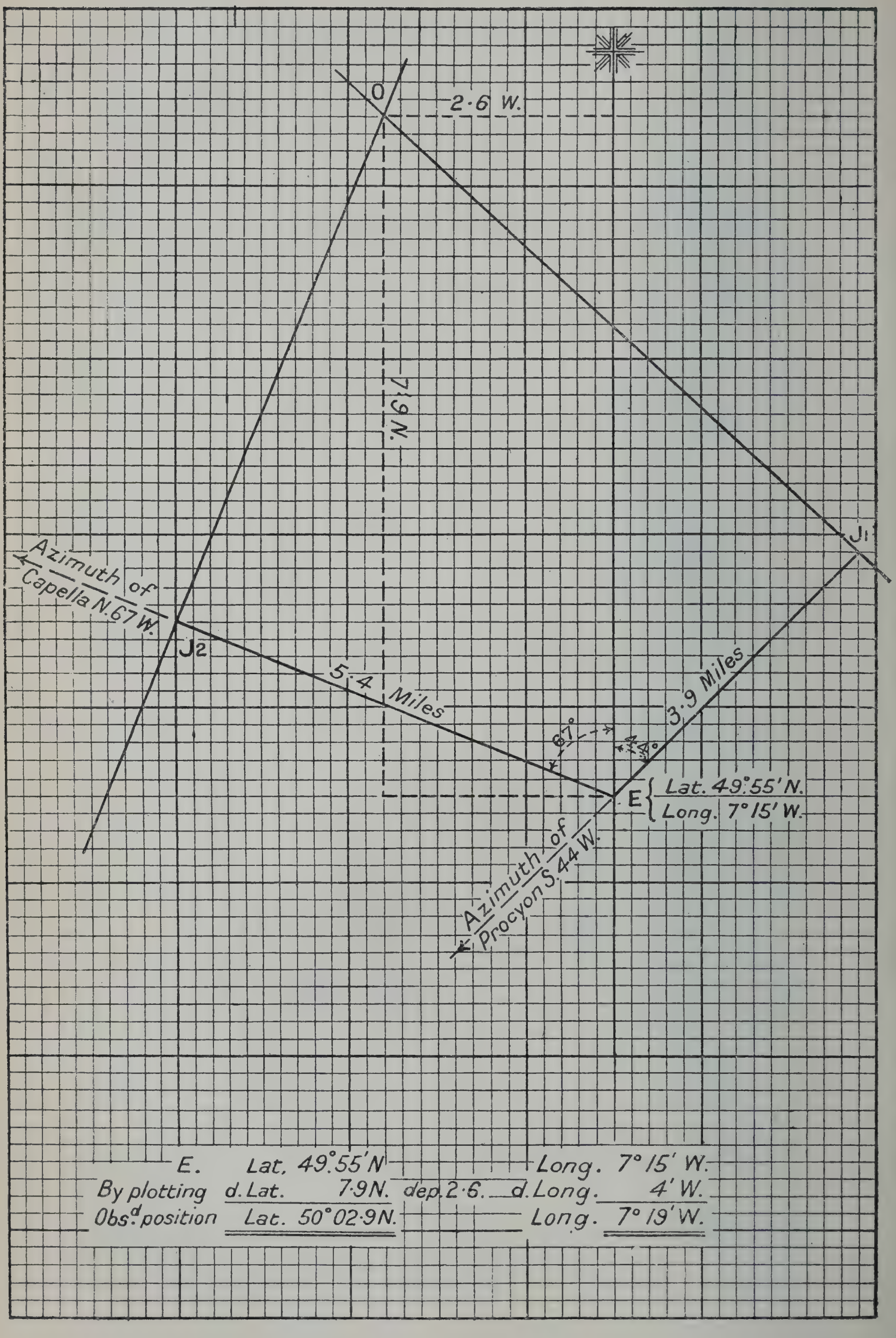

O
2·6 W.
7·9 N.
J1
Azimuth of Capella N.67 W.
J2
5·4 Miles
3·9 Miles
67°
44°
E
Lat. 49°55′ N.
Long. 7°15′ W.
Azimuth of Procyon S.44 W.
E. Lat. 49°55′ N Long. 7°15′ W.
By plotting d. Lat. 7·9 N. dep. 2·6. d. Long. 4′ W.
Obs.d position Lat. 50°02·9 N. Long. 7°19′ W.

Fig. 88.

Example (2) :—Position by calculation. Simultaneous observations.

On March 17th, 1914, at about $7^h\ 25^m$ A.M. (S.M.T. nearly), in estimated position Lat. 36° 50′ N., Long. 140° 03′ W., the deck watch was slow on G.M.T. $5^h\ 20^m\ 15^s$. I.E., + 1′ 30″. H.E., 40 ft.

The following observations were taken to determine the position of the ship :—

Deck watch	$11^h 25^m 11^s{\cdot}5$	Obs. alt. ☉	14° 17′ 00″
” ”	11 27 38	Obs. alt. ☽	16 23 00

S.M.T.	$19^h 25^m$ Mar. 16th	Obs. alt. ☉	14° 17′ 00″	Dec. 1° 29′·5 S.
Long.	9 20 12^s (W).	I.E.	+ 1 30	
				Eq. T. $8^m 36^s{\cdot}8$ + to A.T.
	28 45		14 18·5	
	24 00	Cor.	+ 6·3	
G.D.	4 45 Mar. 17th		14 24·8	
		True *z*	75 35·2	

D.W.	$11^h 25^m 11^s{\cdot}5$
Slow	5 20 15
	16 45 26·5
	12 00 00
G.M.T.	4 45 26·5
Long.	9 20 12 (W).
M.T.P.	19 25 14·5
Eq. T.	—8 36·8

H.	19 16 37·7	*L* hav	9·52624
Lat.	36° 50′ N.	*L* cos	9·90330
Dec.	1 29·5 S.	*L* cos	9·99985
(*L* + *D*)	38 19·5	*L* hav *θ*	9·42939

Nat hav *θ*	·26878	
Nat hav (*L* + *D*)	·10775	
Nat hav *z*	·37653	Calc. *z* 75° 42′·2
		True *z* 75 35 ·2

Intercept - - - 7′ towards

Azimuth from Tables N. 103° E. (S. 77° E.)

Estimated position -	Lat. 36° 50′ N.		Long. 140° 03′ W.
Intercept S. 77° E. 7′	*d* Lat. 1·6 S.	Dep. 6′·8	*d* Long. 8·5 E.
J - - - -	Lat. 36 48·4 N.		Long. 139 54·5 W.

The latitude and longitude of *J* is now used as the latitude and longitude of the estimated position (§ 113).

D.W. -	11h 27m 38s	Obs. alt. ☾	16° 23′ 00″	R.A.	16h 37m 25s
Slow -	5 20 15	I.E. -	+ 1 30		+ 2 03
	16 47 53		16 24·5		16 39 28
	12 00 00	Cor. -	− 9·4		
G.M.T.	4 47 53 Mar. 17th		16 15·1	Dec.	27° 25′·6 S.
	24 00 00	S.D. -	− 16·0		+ 3·8
	28 47 53		15 59·1		27 29·4 S.
Long.	9 19 38(W.)	Par.	+ 55·8		
			+ 0·5	S.D.	16′ 01″
M.T.P.	19 28 15				− 3
R.A.M.S.	23 37 31·3 +		16 55·4		
For 40m	+ 6·6				15 58
,, 8m	+ 1·3	True z	73 04·6	Aug.	+ 5
	43 05 54·2			S.D.	16 03
	24 00 00				
				Hor. par.	58 41
R.A.M.	19 05 54·2				− 10
R.A.	16 39 28 −				
					58 31
H. -	2 26 26·2	L hav	8·99403		
Lat. -	36° 48′·4 N.	L cos	9·90344		
Dec. -	27 29·4 S.	L cos	9·94796		
$(L + D)$	64 17·8	L hav θ	8·84543		
		Nat hav θ	·07006		
		Nat hav $(L + D)$	·28317		
		Nat hav z	·35323	Calc. z	72° 55′·7
				True z	73 04·6

Intercept - 8·9 away

Azimuth from Tables N. 146° W. (S. 34° W.)

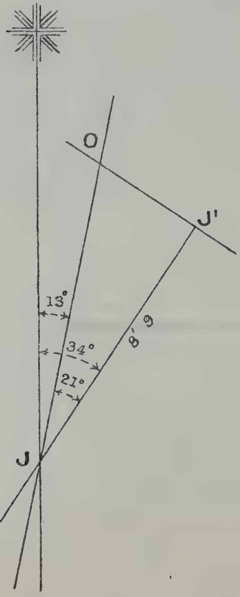


FIG. 89.

The position lines should now be sketched as shown in Fig. 89, where *OJ* is the first position line, *JJ′* the second intercept, and *OJ′* the second position line. The position of *O* can be calculated if we know the length and direction of *JO*. Now *JO* is in the direction of the first position line, N. 13° E. and $JO = JJ' \sec OJJ' = 8{\cdot}9 \sec 21°$, which is found by the traverse table to be 9·5 miles. Thus, if we apply 9·5 miles in a direction N. 13° E. to the latitude and longitude of *J*, we can find the latitude and longitude of *O*.

J Lat. - - -	36° 48′·5 N.		Long.	139° 54′·5 W.
N. 13° E. 9′·5 *d* Lat.	9 ·3 N.	Dep. 2′·1	*d* Long.	2 ·7 E.
Ship's position Lat. -	36 57·8 N.		Long.	139 51 ·8 W.

Example (3):—Position by calculation and by plotting on the chart. Successive observations.

On March 21st, 1914, at about 8^{h} A.M. (S.M.T. nearly), in estimated position Lat. 49° 58′·2 N., Long. 7° 31′ W., the deck watch was slow on G.M.T. $5^{\text{h}}\ 20^{\text{m}}\ 15^{\text{s}}$. I.E., + 1′ 30″. H.E., 40 ft.

The following observations were taken :—

Deck watch	$3^{\text{h}}\ 09^{\text{m}}\ 10^{\text{s}}$	Obs. alt. $\underline{\odot}$ 17° 29′ 50″
	3 09 44	17 34 50
	3 10 06	17 38 10

The ship was steaming S. 32° E. (comp.) at 11 knots, and at about $11^{\text{h}}\ 15^{\text{m}}$ A.M. (S.M.T. nearly) the following observations were taken :—

Deck watch	$6^{\text{h}}\ 25^{\text{m}}\ 48^{\text{s}}$	Obs. alt. $\underline{\odot}$ 39° 08′ 10″
	6 26 12	39 09 00
	6 26 33	39 10 10

Required the position of the ship at $11^{\text{h}}\ 15^{\text{m}}$ A.M.

$3^{\text{h}}\ 09^{\text{m}}\ 10^{\text{s}}$	17° 29′ 50″
3 09 44	17 34 50
3 10 06	17 38 10
3 / 29 00	3/102 50
3 09 40	17 34 17

S.M.T.	$20^{h}00^{m}$ Mar. 20th	Obs. alt. ☉	17° 34′ 17″	Dec. 0° 02′·7 S.	
Long.	$30\ 04^{s}$ (W.)	I.E. -	+ 1 30		
				Eq. T. $7^{m}\ 31^{s}·9$ + to A.T.	
G.D.	20 30 Mar. 20th.		17 35·8		
		Cor. -	+ 7·0		
D.W.	$3^{h}\ 09^{m}40^{s}$		17 42·8		
Slow	5 20 15				
		True *z* -	72 17·2		
	8 29 55				
	12 00 00				
G.M.T.	20 29 55				
Long.	30 04 (W.)				
M.T.P.	19 59 51				
Eq. T.	− 7 31·9				

H. -	19 52 19·1	*L* hav	9·42268
Lat. -	49° 58′·2 N.	*L* cos	9·80834
Dec. -	0 02 ·7 S.	*L* cos	10·00000
(*L*+*D*)	50 00·9	*L* hav *θ*	9·23102

Nat hav *θ* - - ·17024
Nat hav (*L* + *D*) ·17869

Nat hav *z* - - ·34893 Calc. *z* 72° 24′·7
True *z* 72 17 ·2

Intercept 7 ·5 towards.

Azimuth from Tables N. 112° E. (S. 68° E.)

Estimated position	Lat. 49° 58′·2 N.		Long. 7° 31′ W.
S. 68° E. 7′·5	*d* Lat. 2 ·8 S.	Dep. 6′·9	*d* Long. 10·8 E.
J - - -	Lat. 49 55 ·4 N.		Long. 7 20·2 W.

Compass course S. 32° E. Run for $3^{h}\ 15^{m}$ at 11 knots is 35′·7
Dev. from table 4 W.

Mag. course - S. 36 E.
Var. from chart 18½ W.

True course - S. 54½ E.

J - -	Lat. 49° 55′·4 N.		Long. 7° 20′·2 W.
S. 54½° E. 35′·7	*d* Lat. 20 ·7 S.	Dep. 29·1	*d* Long. 45·0 E.
Est. Pos. $11^{h}\ 15^{m}$ A.M.	49 34 ·7 N.		Long. 6 35·2 W.

$6^{h}\ 25^{m}\ 48^{s}$	39° 08′ 10″
6 26 12	39 09 00
6 26 33	39 10 10
3/ 78 33	3/ 27 20
6 26 11	39 09 07

S.M.T.	23^h 15^m Mar. 20th	Obs. alt. $\underline{\odot}$	39° 09′ 07″ Dec. 0° 00′·5 N.
Long.	26 21^s (W).	I.E. -	+ 1 30
			Eq. T. 7^m 29^s·5 + to A.T.
G.D. -	23 41 Mar. 20th		39 10·6
D.W. -	6^h 26^m 11^s	Cor. -	+ 8·6
Slow -	5 20 15		
			39 19·4
	11 46 26		
	12 00 00	True z. -	50 40·6
G.M.T.	23 46 26		
Long.	26 20·8 (W.)		
M.T.P.	23 20 05·2		
Eq. T. -	— 7 29·5		
H. -	23 12 35·7	L hav	8·02767
Lat. -	49° 34′·7 N.	L cos	9·81184
Dec. -	0 00·5 N.	L cos	10·00000
$(L - D)$	49 34·2	L hav θ	7·83951
	Nat hav θ -	·00691	
	Nat hav $(L - D)$	·17575	
	Nat hav z -	·18266	Calc. z 50° 36′·2
			True z 50 40·6
		Intercept -	4·4 away.

Azimuth from Tables N. 164° E. (S. 16° E.)

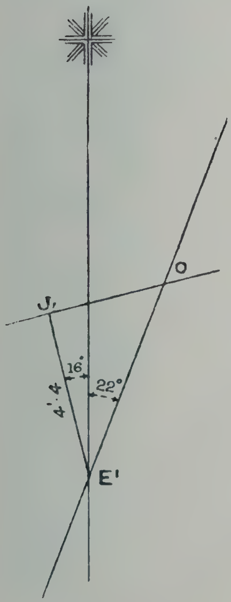


FIG. 90.

$$E'O = E'J' \sec OE'J'$$
$$= 4'{\cdot}4 \sec 38°$$
$$= 5'{\cdot}6 \text{ (from traverse table).}$$

Estimated position at $11^h\ 15^m$ A.M. :—

	Lat. 49° 34′·5 N.	Long. 6° 35′·2 W.
N. 22° E. 5′·6	*d* Lat. 5·2 N. Dep. 2′·1	*d* Long. 3·3 E.
Position at $11^h\ 15^m$ A.M.	Lat. 49 39·7 N.	Long. 6 31·9 W.

Fig. 91 shows the method of finding the position by plotting on the chart.

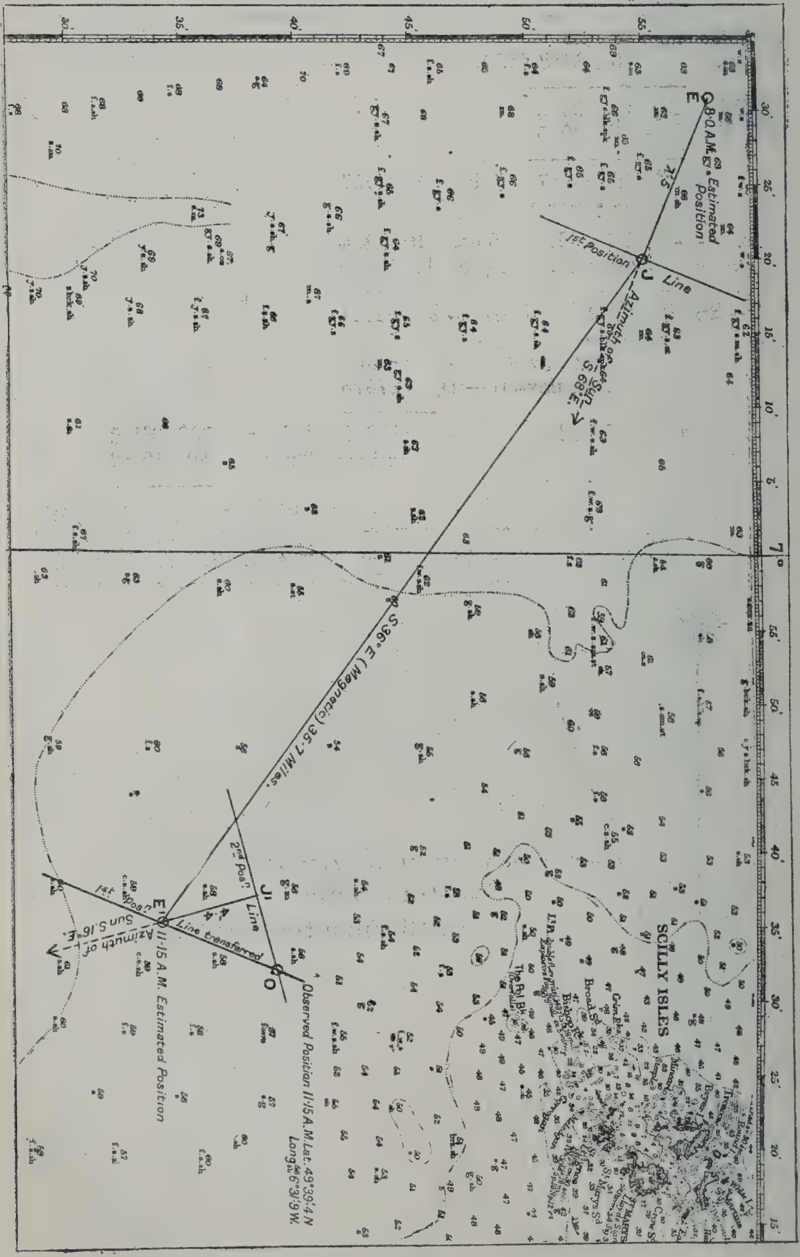

8.0 A.M. Estimated Position
E
7.5
1st Position Line
J
Azimuth of Sun S 68°E.
S 36° E (Magnetic) 35.7 Miles.
2nd Posn Line
J1
4.4
E1
1st Posn Line transferred
Azimuth of Sun S.16°E.
11-15 A.M. Estimated Position
O
Observed Position 11·15 A.M. Lat. 49°39′·4 N Long. 6°31′·9 W.
SCILLY ISLES
30′
35′
40′
45′
50′
55′
7°

FIG. 91.

117. Error in a position due to error in the observed altitudes.—Suppose that we can estimate that the observed altitude is too great or too small by an amount not exceeding *n* minutes, then the true zenith distance *XCJ*, Fig. 92, is too small or too great by an amount not exceeding *n* minutes, so that the actual zenith distance, at the observer, must lie between *XCB* and *XCA*, *JA* and *JB* being each equal to *n* nautical miles. Therefore the observer's position lies between the two circles of position whose radii are *UB* and *UA*.

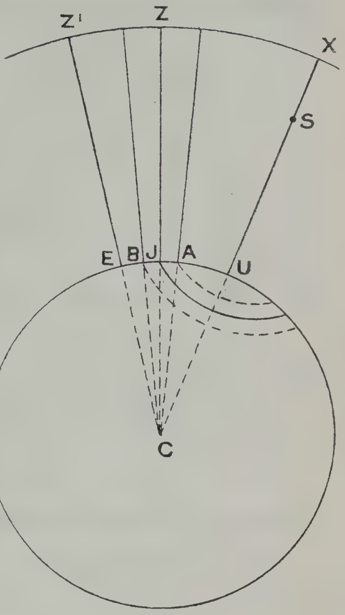


FIG. 92.

Consequently the observer's position on the chart lies between two parallel position lines situated on either side of the position line obtained from the observation, and at a distance of *n* miles from it. In Example (1) (§ 116), suppose that we assume that the altitudes were each not more than 2′ in error, due to uncertainty in the position of the sea horizon or to errors of observation; then, corresponding to the altitude of *Procyon*, the observer's position lies between the position lines *CD* and *FG*, Fig. 93, and, corresponding to the altitude of *Capella*, his position lies between the position lines *CF* and *DG*. It follows, therefore, that his position lies within the parallelogram *CDGF*, which may be referred to as his area of position, and, although *O* is the most probable position of the ship, if a course has to be shaped to clear a danger, consideration should be given to the possibility of the ship being situated anywhere within the area of position. For example, suppose that it is desired to shape a course up Channel to pass at least 5 miles off the Bishop Rock; it will be seen that, if the course is shaped from the point *G*, it will have been shaped from the most disadvantageous position and is the safest to steer.

In a case where it is possible to assume that in one altitude the error does not exceed m', and that in the other it does not exceed n', the parallelogram may be constructed in a similar manner by drawing the sides at their respective distances (m' and n') on either side of the position lines obtained from the observations.

Now the error, to which an altitude is most liable, is that due to the uncertain position of the sea horizon, and this may to some extent be guarded against by taking observations of four heavenly bodies, A, B, C, D, the azimuths of A and B and of C and D being approximately opposite. In this case it is probable

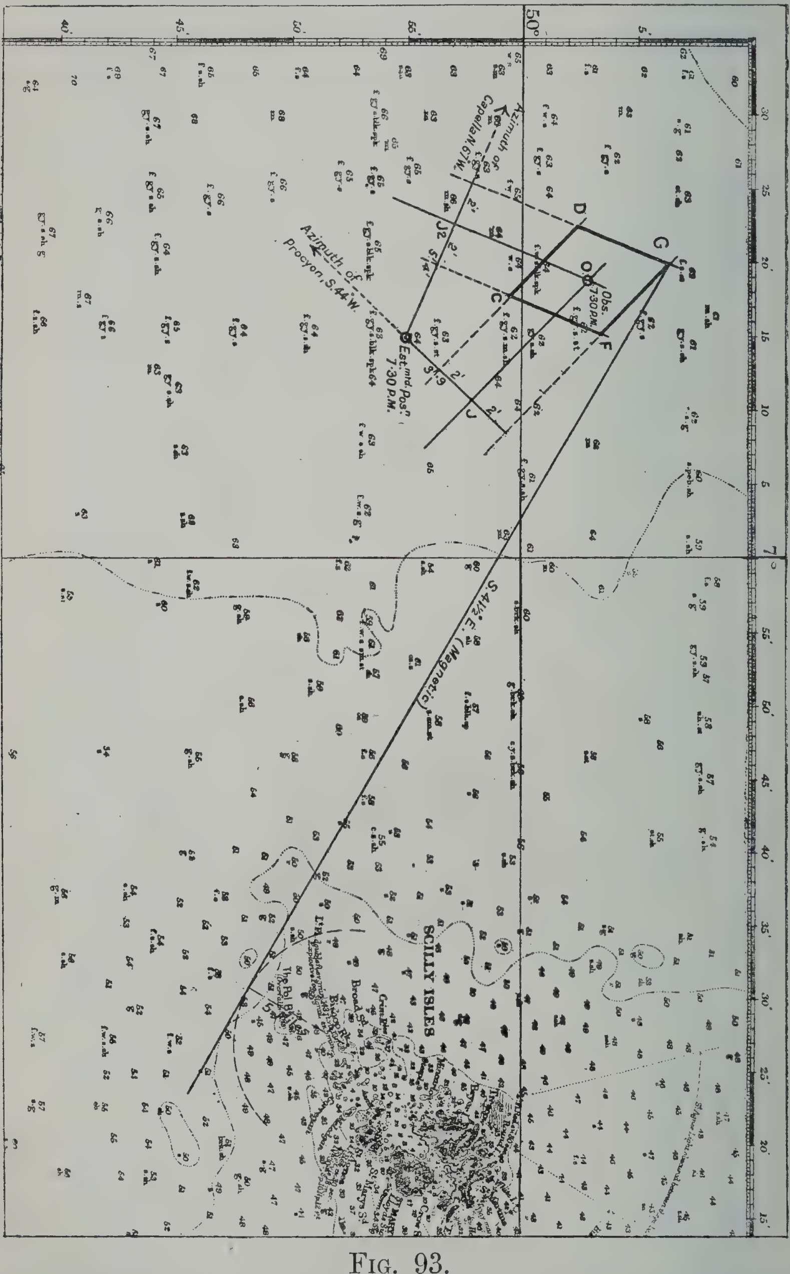


FIG. 93.

that the four position lines will form a quadrilateral figure, when the most probable position of the ship is at a central point within the quadrilateral.

When three heavenly bodies are observed, and the position lines form a cocked hat, the most probable position of the ship is, in the absence of all information, within the triangle at a point whose distances from the three sides are proportional to the lengths of the sides respectively.

If it be assumed that the errors in the three observed altitudes are equal and in the same direction it is possible to give a geometrical construction for finding the position of the ship, but one can never be certain that the dip of the sea horizon is the same in all directions, and therefore it is never safe to assume that the error in each position line is the same. If the ship is in the vicinity of land, position lines, parallel to the sides of the triangle, should be drawn external to the triangle, and at distances equal to the maximum estimated error; the course should then be shaped by considering the relative position of the land and the triangle thus formed.

118. Error in a position due to uncertainty of the error of the deck watch.—In Fig. 94 let *O* be the observer at the intersection of two circles of position. Then, if there is an error in the G.M.T. as found from the deck watch, the observer, instead of regarding the meridian of Greenwich in its true position *PGP′*, regards it at some position *PG′ P′*, the angle *GPG′* being the error in the G.M.T. The consequence of this is that, since the error affects both observations equally, the observer regards himself as being at the intersection of the two circles of position (shown in broken lines in the figure), which are of the same radii as the former but displaced in longitude an amount equal to *GPG′*, which is the error in the G.M.T. Thus *O* is moved East or West in longitude by an amount equal to the error, and the position lines are moved parallel to themselves through the same distance in longitude. The direction in which *O* is moved will be seen from the formula for the longitude of the geographical position of a heavenly body (§ 109), (W. Long. = R.A.M.S. + G.M.T. − R.A. ✱), from which it is obvious that, if the G.M.T. is greater than it should be, *O* is too far to the Westward, and if the G.M.T. is smaller than it should be, *O* is too far to the Eastward. Thus, in

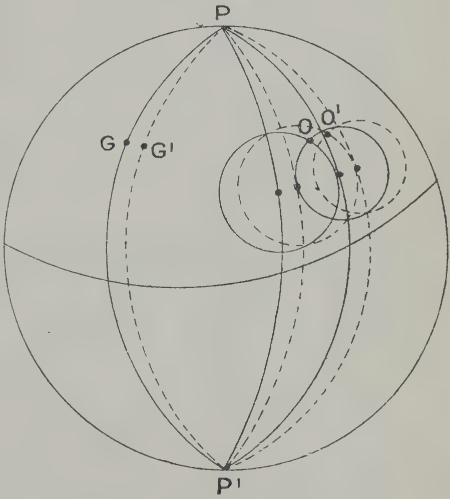


Fig. 94.

Fig. 95, if O is the position obtained from the two position lines shown, and there is an unknown error in the observed time the maximum value of which is estimated to be $\pm dH$, the ship will lie on the line $O'O''$ where O' and O'' differ in longitude from O by dH.

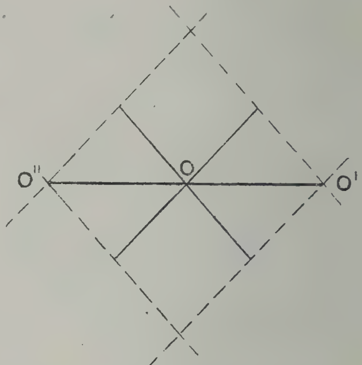


Fig. 95.

In Example (1) (§ 116) suppose that the error in the deck watch was estimated to lie between 2h 29m 30s slow and 2h 29m 38s slow. The position of the ship was calculated using an error 2h 29m 34s slow, and was found to be Lat. 50° 2′·8 N. Long. 7° 19′ W. and we see that, due to this possibility of error in the G.M.T., the ship's position lies on the arc of a parallel of latitude 50° 2′·8 N. between the longitudes 7° 18′ W. and 7° 20′ W. In these circumstances, if a course has to be shaped to make the land, it should as a rule be shaped from the most disadvantageous position on the arc of the parallel named, but if shaped from the most probable position of ship, O, it should be borne in mind that the actual position of the ship may be nearer to the shore than the estimated position.

119. Error in a position due to error in the observed altitudes and to uncertainty of the error of the deck watch.—It has been shown above that if there is an error in each of the observed altitudes the observer is within a certain parallelogram; it has also been shown that if there is an error in the G.M.T. the observer is on a parallel of latitude intersected between two particular meridians; therefore, if these two errors coexist, the observer is somewhere within an area traced out by moving the parallelogram East and West within the limits of longitude above-mentioned, as shown in Fig. 96 which refers to Example (1) (§ 116).

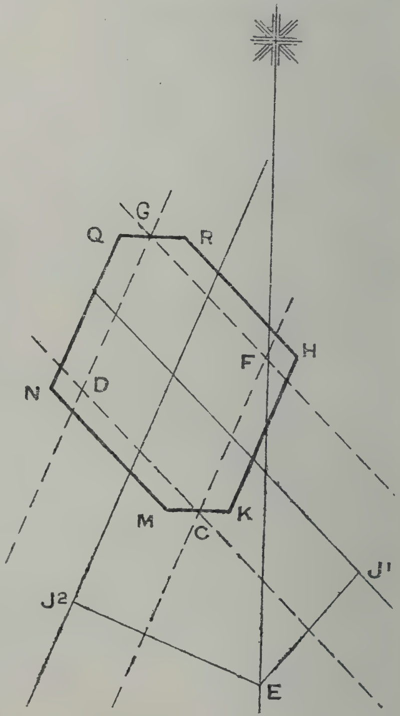


Fig. 96.

120. Error in a position due to error in the reckoning between the observations.—When there is an interval of time between the two observations for finding a position, we transfer the position line obtained at the first observation, parallel to itself, through a distance equal to the run of the ship between the two observations; then, if the reckoning in the interval is correct, the ship is on the transferred position line at the time of the second observation. In Fig. 97, *E* is the estimated position at the first observation, *E′* the estimated position at the second observation, *E′ O* the first position line transferred, so that, if the course and distance made good have been correctly estimated, the ship is somewhere on the line *E′O* at the time of the second observation.

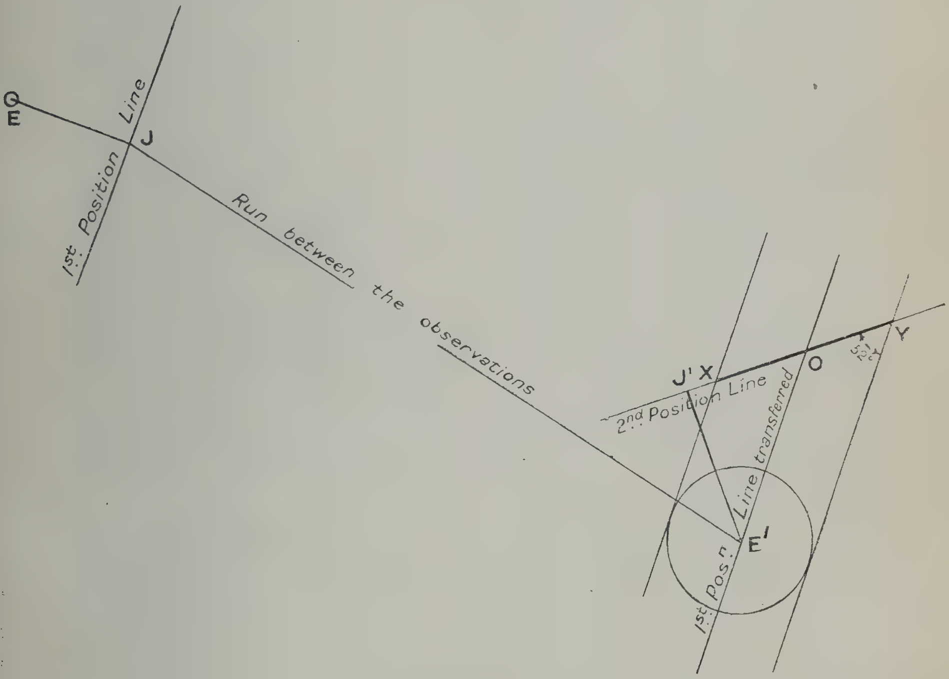


FIG. 97.

Let us assume that it is possible for the reckoning to be in error by an amount not exceeding x°/ₒ of the distance run, then the transferred position line at the second observation may lie on either side of *E′* and at a distance from it not exceeding x °/ₒ of the distance run. Therefore, if we describe a circle with centre *E′*, and radius $\frac{x}{100} \times$ run, and draw two tangents to this circle parallel to the first position line, the ship must lie between these tangents.

Let the second observation, worked out with E' as estimated position, give a position line which intersects the tangents in X and Y, then the ship must lie on the line XY intercepted between the two tangents. Therefore, unless the reckoning between the two observations is absolutely correct, the information from two successive observations is that the ship is situated on a terminated portion of the second position line, the length of which varies directly as the error in the run and inversely as the sine of the angle between the first and second position lines.

In Example (3) (§ 116) let us assume that it is possible for the reckoning to be in error by an amount not exceeding 5 per cent. of the distance run, (35·7 miles), then the radius of the circle mentioned above is 1·8 miles. The ship is therefore on the second position line XY, which lies in the direction $\begin{smallmatrix}\text{N.}\\\text{S.}\end{smallmatrix}\,74^\circ\,\begin{smallmatrix}\text{E.}\\\text{W.}\end{smallmatrix}$ and passes through the point O, the position of which has been found to be Lat. 49° 39′·7 N., Long. 6° 31′·9 W.

Now $XO = OY = 1'\cdot8 \text{ cosec } 52^\circ = 2\cdot28$ miles.

Therefore the length of the line XY, somewhere on which the ship is situated, is 4·56 miles.

121. Error in a position due to error in the reckoning between the observations, and to the error in the observed altitudes.—If, in the last example, there had been a possibility of error in each altitude not exceeding 2′, it is necessary to draw lines ST and UV (Fig. 98) parallel to the tangents and at distances 2 miles

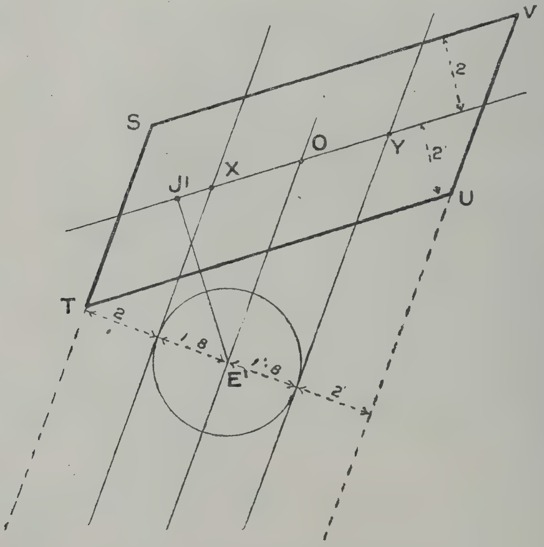


Fig. 98.

from them, measured away from the circle, and to draw lines *SV* and *TU* parallel to and on either side of *XY* and 2 miles from it. The area of position, taking the two errors into account, is the parallelogram *STVU*.

122. Error in a position due to error in the reckoning between the observations, to error in the observed altitudes, and to uncertainty of the error of the deck watch.—If, in addition to the possible errors in the reckoning and altitude just mentioned (§ 120–121), there is a possible error of four seconds in the G.M.T., it is obvious that the area of position is the area traced out by moving the parallelogram *STUV* (§ 121) East and West through 1′ of longitude.

123. Particular case of very large altitudes.—The following method of plotting the position lines, although it can seldom be applied, brings out the theory of position lines very clearly. When in low latitudes an observation is taken of a body which is passing nearly overhead, the circle of position may be drawn as a circle on the Mercator's chart; the centre of the circle is the geographical position of the body, and the radius is the true zenith distance. When two observations are taken, two circles of position may be drawn, and the position of the ship is at one or other of their points of intersection; to determine which of the points of intersection is the position of the ship, the observer should note whether he is North or South of the body as it passes his meridian.

If there is a run of the ship between the two observations, as is generally the case, the position line at the first observation must be transferred for the run of the ship; this is done by transferring the geographical position at the first observation through a distance equal to the run of the ship and in the same direction.

The following example, in which there are three observations and consequently three circles of position, shows how the position of the ship is found, the circles being drawn on squared paper.

In Fig. 99, *A*, *B* and *C* are the three geographical positions of the sun at the times of the three observations, their latitudes and longitudes being found in the manner shown below; *AD* is the run of the ship between the first and third observations, that is N. 60° W. 1′·5; *BE* is the run of the ship between the second and third observations, that is N. 60° W. 0′·6. The three circles are described with centres *D*, *E* and *C*.

Example:—On April 28th, 1914, at about $11^h\ 55^m$ A.M. (S.M.T. nearly) in estimated position Lat. 14° 30′ N., Long. 85° 10′ E, the deck watch was slow on G.M.T. $2^h\ 12^m\ 34^s$ I.E., + 1′ 30″; H.E., 40 feet. The ship was steaming N. 60° W. (true) 18 knots.

The following observations were taken to determine the position of the ship, and the observer was North of the body as it passed his meridian.

Deck watch	$4^h\ 01^m\ 40^s$	$\underline{\odot}$ 89° 03′ 00″
,, ,,	4 04 24	,, 89 15 10
,, ,,	4 06 34	,, 88 57 50

S.M.T. $23^h\ 55^m$ Apr. 27th Dec. 13° 53′·9 N.
Long. 5 41 (E.) Eq. T. $2^m\ 25^s$·9 – to A.T.

G.D. 18 14 Apr. 27th.

D.W. -	$4^h 01^m 40^s$
Slow -	2 12 34
	6 14 14
	12 00 00
G.M.T. -	18 14 14
Eq.T. -	+ 2 25·9
G.A.T. -	18 16 39·9
	24 00 00
	5 43 20·1
Long. of A.	85° 50′ E.

Geographical pos. at 1st Obs. { Lat. 13° 53′·9 N. Long. 85° 50′ E.

D.W. at 1st Obs.	$4^h\ 01^m\ 40^s$	
D.W. at 2nd Obs.	4 04 24	
Interval - -	2 44	= 41′ (W.) Dep. 39′·8 (W.).
D.W. at 1st Obs.	4 01 40	
D.W. at 3rd Obs.	4 06 34	
Interval - -	4 54	= 73′·5 (W.) Dep. 71′·3 (W.).

Run between 1st and 3rd Obs.

$$\text{N. } 60^\circ \text{ W. } \frac{18 \times 4\cdot9}{60} = \text{N. } 60^\circ \text{ W. } 1'\cdot47.$$

Run between 2nd and 3rd Obs.

$$\text{N. } 60^\circ \text{ W. } \frac{18 \times 2\cdot2}{60} = \text{N. } 60^\circ \text{ W. } 0'\cdot66.$$

Obs. alt. $\underline{\odot}$ -	89° 03′ 00″	89° 15′ 10″	88° 57′ 50″
I.E. - -	+ 1 30	+ 1 30	+ 1 30
	89 04·5	89 16·7	88 59·3
Cor. - -	+ 9·7	+ 9·7	+ 9·7
	89 14·2	89 26·4	89 09·0
True *z*. (Radii) -	45·8	33·6	51·0

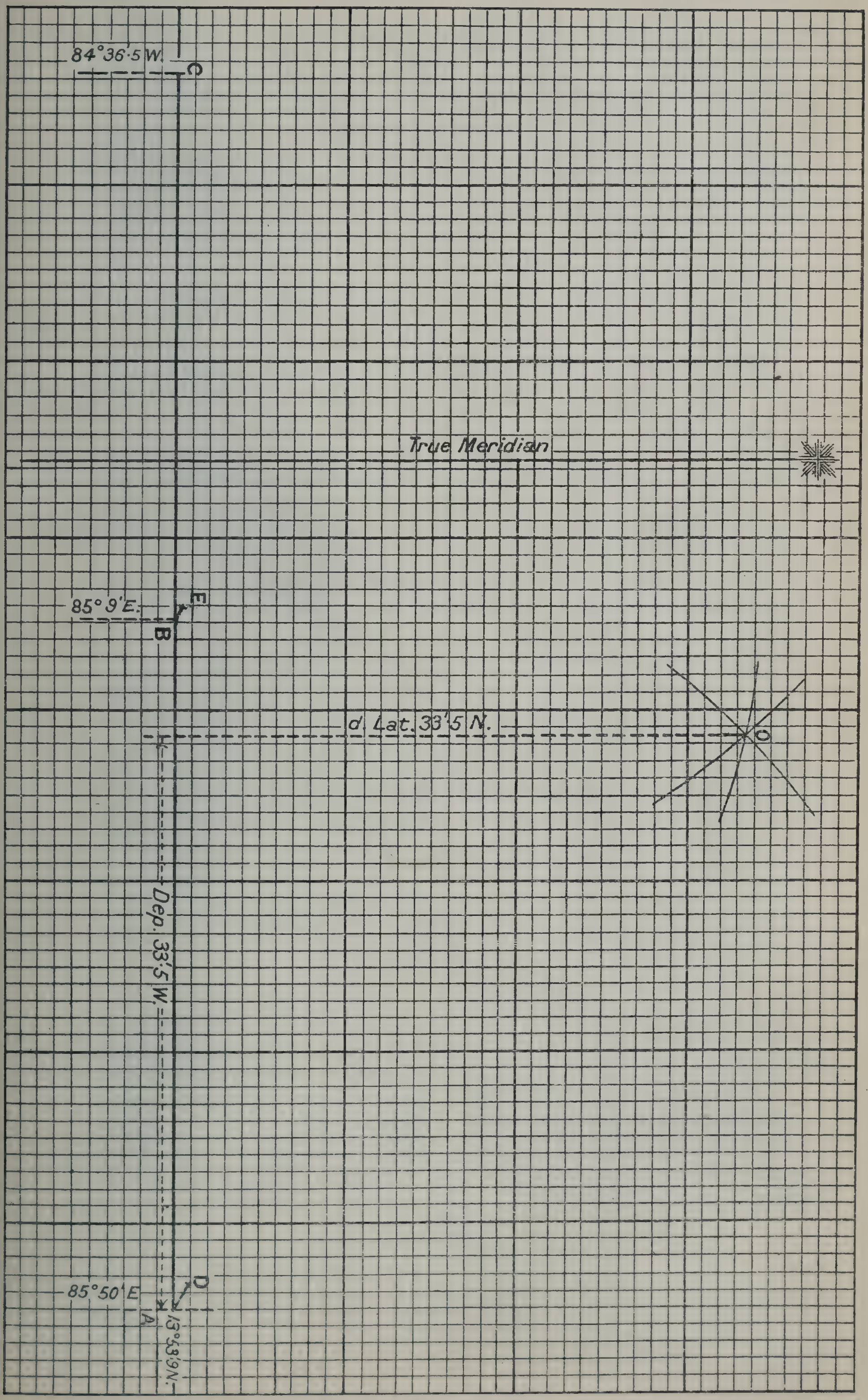

84°36'·5 W.
C
True Meridian
85° 9' E.
E
B
d. Lat. 33'·5 N.
O
Dep. 33'·5 W.
85°50' E
D
A
13°53'·9 N.

Fig. 99.

Draw a line on the squared paper, Fig. 99, to represent the parallel of 13° 53′·9 N., which is the latitude of the three geographical positions, and on this line select a point A to represent the geographical position at the 1st observation.

On any convenient scale, 10 miles to the inch in this example, plot the geographical positions at the second and third observations by means of the departures found above, and mark them B and C respectively.

From A lay off AD, N. 60° W., 1·47 miles, and from B lay off BE, N. 60° W., ·66 miles.

With centres D, E, and C describe circles of radii 45′·8, 33′·6, and 51′ respectively. The intersection of these three circles at O is the position of the ship.

Measure the *d* Lat. and Dep. between O and A, convert the Dep. into *d* Long. and so find the latitude and longitude of the ship.

Lat. A	13° 53′·9 N.		Long. A	85° 50′ E.
d Lat.	33 ·5 N.	Dep. 33′·5 (W.)	*d* Long.	34·4 (W.)
Lat. O	14 27 ·4 N.		Long. O	85 15·6 E.

124. Position by astronomical and terrestrial position lines.—(1) By combination of an astronomical position line and a line of bearing.

Suppose that a bearing of a terrestrial object is taken at the same time as an observation of a heavenly body, then obviously the position of the ship is at the intersection of the line of bearing and the astronomical position line. The accuracy of this position depends on the angle of intersection of the two position lines, so that the bearing of the object and the heavenly body should be as nearly as possible the same or opposite to one another.

The position can be obtained from two such observations when there is a run in the interval between them, the position in this case being obtained as explained above by transferring the first position line for the run of the ship.

(2) By an astronomical position line and a sounding.

If a sounding is taken at the same time as an observation of a heavenly body an approximate position can be obtained, provided that the soundings shown on the chart are such that the contour line of the depth obtained can be drawn with confidence, and that its mean direction makes a good angle with the astronomical position line. The depth should be verified by two or more soundings, and these should be corrected as explained in Part IV.

CHAPTER XIV.

OTHER METHODS OF DETERMINING AN ASTRONOMICAL POSITION LINE.

125. Meridian passages of heavenly bodies.—Besides the general method of determining an astronomical position line, there are various other methods which have advantages over the general method in special circumstances, and these will be described in this chapter. We will first explain the method of obtaining the position line from the altitude of a heavenly body when the body is on the observer's meridian, but, before doing so, we must show how to find the observer's mean solar time at which the observation should be taken.

A body is said to have its upper meridian passage when it passes the observer's celestial meridian, and to have its lower meridian passage, sometimes called its meridian passage below pole, when it passes the meridian which differs from that of the observer by 180°. In this book, whenever meridian passage is mentioned, the upper meridian passage is to be understood unless otherwise stated.

(*a*) *The Sun.*—The sun passes the meridian of any place at apparent noon at that meridian, and has its lower meridian passage at apparent midnight. In order to find the time by the chronometer or by the ship's clocks at which the sun passes the meridian, we proceed as follows:—

Example:—Required the time by ship's clocks on March 3rd, 1914, at which the sun will pass the meridian of a place in longitude 25° 17′ E., the ship's clocks being set to Eastern European time which is 2 hours fast on G.M.T.

S.A.T. 24^{h} 00^{m} Mar. 2nd. Eq. T. 12^{m} 15^{s} + to A.T.
Long. 1 41 (E.)

G.D. 22 19 Mar. 2nd.

S.A.T. 24^{h} 00^{m}
Long. 1 41 (E.)
G.A.T. 22 19
Eq. T. + 12
G.M.T. 22 31
Clock 2 00 fast on G.M.T.
24 31
24 00

0 31 P.M. Time by ship's clocks.

(*b*) *The Stars.*—When a star is on the observer's meridian the right ascension of the star is equal to the right ascension of the meridian, and the latter, by the formula in § 97, is equal to R.A.M.S. + S.M.T.

Therefore,

R.A. ✱ (when on the meridian) = R.A.M.S. + S.M.T. or
S.M.T. = R.A. ✱ − R.A.M.S.

Now the R.A. of a star may be taken directly from the Almanac. The R.A.M.S. should be taken out for G.M. Noon, and then with these two elements we can find an approximate S.M.T. By applying the longitude in time to this approximate S.M.T. we can find the Greenwich date, with which to correct the R.A.M.S. and then find a more correct S.M.T.

Example:—Find the S.M.T. at which Canopus (α Argus) will pass the observer's meridian (Long. 45° W.) on March 5th, 1914.

R.A.✱	$6^h\ 22^m\ 03^s$
Add	24 00 00
	30 22 03
R.A.M.S.	22 49 33
S.M.T.	7 32 30 (approx.)
Long.	3 00 00 (W.)
G.D.	10 32 30 Mar. 5th.

R.A. Canopus $6^h\ 22^m\ 03^s$

R.A.M.S.	$22^h\ 49^m\ 33^s{\cdot}3$
Add for 10^h	1 38 ·6
" " 30^m	4 ·9
" " 2^m	·3
	22 51 17 ·1

R.A.✱ + 24^h	$30^h\ 22^m\ 03^s$
R.A.M.S.	22 51 17·1
S.M.T.	7 30 45·9

Therefore Canopus will pass the meridian at approximately $7^h\ 31^m$ P.M., March 5th.

Since the right ascensions of the stars are practically constant, and the daily increase of the R.A.M.S. ($3^m\ 56^s$) is nearly 4 minutes per day, it follows that the stars cross the meridian of any particular place about 4 minutes earlier every day.

When a star passes the meridian below pole, its R.A. differs by 12 hours from that of the meridian. In Fig. 100, since right ascension is measured to the Eastward,

$$♈ PZ = ♈ PX + 12 \text{ hours.}$$

$$\therefore \text{R.A.M.} = \text{R.A.✱} + 12 \text{ hours.}$$

Therefore, since R.A.M. = R.A.M.S. + S.M.T. we have

$$\text{S.M.T.} = \text{R.A.✱} + 12 \text{ hours} - \text{R.A.M.S.}$$

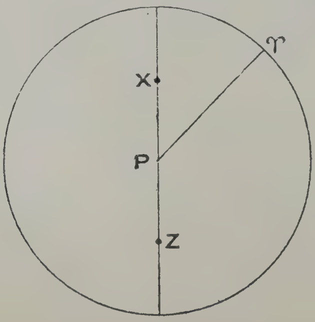


FIG. 100.

Example :—Find the S.M.T. at which Canopus will pass the observer's meridian (Longitude 45° W.) below pole on the night of March 5th, 1914.

R.A.✱	6^h	22^m	03^s	
Add	24	00	00	
	30	22	03	
R.A.M.S.	22	49	33	
S.M.T.	7	32	30	(approx.)
Add	12	00	00	
S.M.T.	19	32	30	(approx.)
Long.	3	00	00	(W.)
G.D.	22	32	30	Mar. 5th.

R.A. Canopus	6^h	22^m	03^s.
R.A.M.S.	22	49	33·3
Add for 22^h		3	36·8
„ „ 30^m			4·9
„ „ 2^m			·3
	22	53	15·3

R.A.✱+24^h	30^h	22^m	03^s
R.A.M.S.	22	53	15
	7	28	48
Add	12	00	00
S.M.T.	19	28	48

Therefore Canopus will pass the meridian below pole at approximately 7^h 29^m A.M., March 6th.

It is sometimes desirable to find what stars pass the observer's meridian above and below pole between two given times; in this case we proceed as follows.

Example :—It is required to find what stars of the first magnitude pass the meridian of 45° W. on March 11th above, and below pole, between the hours of 5^h and 6^h P.M. (S.M.T.)

S.M.T.	5^h 00^m	Mar. 11th	S.M.T.	6^h 00^m	Mar. 11th.
Long.	3 00	(W.)	Long.	3 00	(W.)
G.M.T.	8 00	Mar. 11th	G.M.T.	9 00	Mar. 11th.
R.A.M.S.	23 15		R.A.M.S.	23 15	
S.M.T.	5 00		S.M.T.	6 00	
	28 15			29 15	
	24 00			24 00	
R.A.M.	4 15		R.A.M.	5 15	

Therefore, since the R.A. ✱ (when on the meridian) = R.A.M., we require the names of all stars of the first magnitude whose R.A.s lie between the two values of the R.A.M. just found. On inspection of the Almanac, they will be found to be Aldebaran (α Tauri), Capella (α Aurigæ), and Rigel (α Orionis).

If 12 hours are added to each of the R.A.M.s, we find the R.A. of the meridian below pole at 5^h P.M. and at 6^h P.M. Therefore, all stars of the first magnitude whose R.A.s lie between 16^h 15^m and 17^h 15^m pass the meridian below pole between 5^h P.M. and 6^h P.M. It will be found that there is only one star of the first magnitude, namely Antares (α Scorpii), whose R.A. lies between these limits.

(*c*) *The Moon.*—Owing to the rapid change in the right ascension of the moon, it is a lengthy operation to find the time of the meridian passage by the method which has been given above for the stars, because it is necessary to correct the right ascension of the moon several times. For this reason the times of the upper and lower meridian passages of the moon are tabulated in the Abridged Nautical Almanac, on page II. of every month. The times given are the astronomical G.M.T.'s at which the moon crosses the meridian of Greenwich, and the meridian of 180°.

When two asterisks are shown, as on March 11th and 26th, in the columns headed "Moon's Mer. Pass." it indicates that there is no lower or upper meridian passage respectively on those days.

The moon passes the meridian of Greenwich later each day by the number of minutes in the column headed "diff." Since, in the interval between two meridian passages, the moon passes over 360° of longitude, it follows that the astronomical mean time of meridian passage, over any meridian of West longitude, is later than that over the meridian of Greenwich by $\frac{\text{W. Long.}^\circ}{360^\circ} \times \text{diff.}$ Similarly, the astronomical mean time of meridian passage, over any meridian of East longitude, is earlier than that over the meridian of Greenwich by $\frac{\text{E. Long.}^\circ}{360^\circ} \times \text{diff.}$ In West longitude, the "diff." between the day and the following day should be used; in East longitude, that between the day and the preceding day. A table for $\frac{\text{Long.}^\circ}{360^\circ} \times \text{diff.}$ is given in Inman's Tables under "Correction of moon's meridian passage."

Example:—Find the S.M.T. of the moon's meridian passage on March 9th, 1914, in longitude 60° E.

From the Abridged Nautical Almanac the moon's upper meridian passage takes place at 10^h 15^m on March 9th. The diff. between this and the preceding meridian passage is 55 minutes. With arguments 60° and 55^m, a correction is found in Inman's Tables to be $9^m{\cdot}2$ subtractive.

Mer. Pass.	10^h 15^m March 9th
Correction	$-\ 9{\cdot}2$
S.M.T.	$10\ 05{\cdot}8$ March 9th

or, the moon passes the meridian of 60° E. at S.M.T. 10^h 06^m P.M., March 9th.

(*d*) *The Planets.*—The time of meridian passage of a planet may be found as in the case of a star, but, for convenience, the time of meridian passage of each of the four navigational planets is tabulated on pages XI. and XII. of the Abridged Nautical Almanac for each month. The time given is the astronomical G.M.T. of passage over the meridian of Greenwich, which for all practical purposes may be taken as the mean time of passage over any other meridian. If the exact S.M.T. is required it can be found as in the case of the moon. The difference between the times of two consecutive passages is the change while the planet passes over 360° of longitude; the correction of the meridian passage, therefore, is $\frac{\text{Long}^\circ.}{360^\circ} \times \text{diff.}$

If the times of consecutive meridian passages are getting later, *as in* the case of the moon, add for West longitude and subtract for East longitude; if the times of meridian passages are getting earlier, *contrary to* the case of the moon, subtract for West longitude and add for East longitude.

126. Position line by meridian altitude.—If an observer takes the altitude of a heavenly body when on his meridian, the observer and the geographical position of the body are on the same meridian.

In Fig. 101, let U be the geographical position of the body whose altitude has been observed when the body was on the observer's meridian. Let AB be the circle of position resulting from this observation, then, as the bearing of the body must have been either North or South, the position line must lie East and West through one or other of the points B or A. As the position line in this case runs East and West it coincides with a parallel of latitude, and therefore, from this observation, the latitude of the observer is determined.

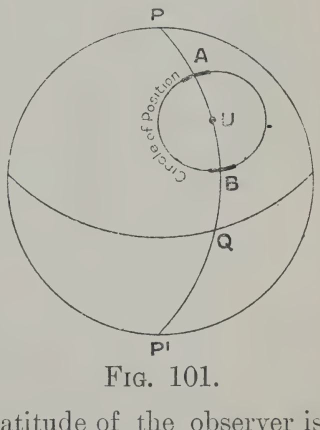


Fig. 101.

Let UQ be the declination of the body, then if the body crossed the meridian North of the observer the latitude of the observer is the latitude of B, and therefore

$$\begin{aligned}\text{Lat.} &= UQ - UB \\ &= \text{Declination} - \text{true zenith distance.}\end{aligned}$$

If the body crossed the meridian South of the observer the latitude of the observer is the latitude of A, in which case

$$\begin{aligned}\text{Lat.} &= UQ + AU \\ &= \text{Declination} + \text{true zenith distance.}\end{aligned}$$

In order to find the latitude from this observation it is advisable to draw a figure, an inspection of which will show at once how the latitude is obtained when the meridian zenith distance (m.z.d.) and the declination of the body are known.

A very convenient figure for this and other problems is obtained by supposing the celestial concave to be projected on to the plane of the observer's rational horizon, from a point at an infinite distance vertically above the zenith. In this case any point of the celestial concave is represented on the plane of the rational horizon by the foot of the perpendicular dropped from that point. Thus, in Fig. 102, the circle NESW represents the rational horizon of a position on the earth whose zenith is *Z*, *NZS* the celestial meridian, *P* the elevated celestial pole, and *WQE* the celestial equator.

If *X* be the true place of a heavenly body, *XX′* is its parallel of declination, *PXD* the celestial meridian of the body, *XD* the declination of the body, *PX* the polar distance, *ZPX* the hour angle, *PZX* the azimuth, *ZX* the zenith distance, *XA* the altitude of the body, and the triangle *PZX* is the astronomical or position triangle.

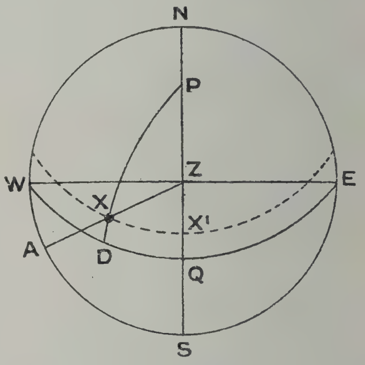


Fig. 102.

The points of the rational horizon where it is intersected by the celestial meridian of the observer are called the North and South points.

The circle of altitude which is at right angles to the celestial meridian of the observer is called the prime vertical, *WZE*, and it intersects the horizon in two points called the East and West points.

Case 1. Latitude N. Declination N. Azimuth S.

From Fig. 103 we have

$$\text{Lat.} = ZQ = ZX + XQ = \text{m.z.d.} + \text{Dec.}$$

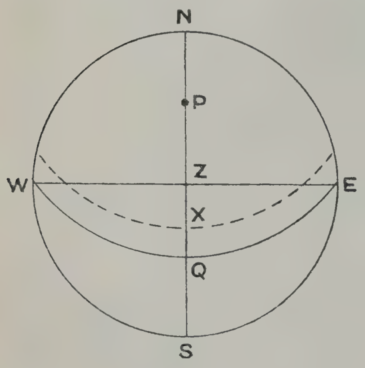


Fig. 103.

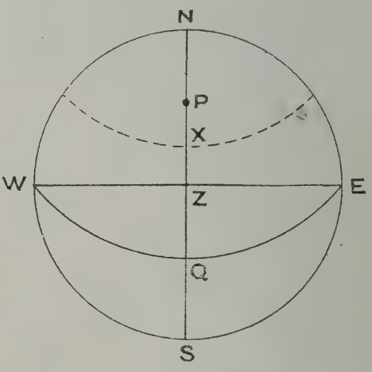


Fig. 104.

Case 2. Latitude N. Declination N. Azimuth N.

From Fig. 104 we have

$$\text{Lat.} = ZQ = QX - ZX = \text{Dec.} - \text{m.z.d.}$$

Case 3. Latitude N. Declination S.

From Fig. 105 we have

$$\text{Lat.} = ZQ = ZX - QX = \text{m.z.d.} - \text{Dec.}$$

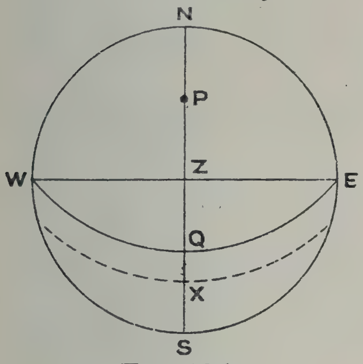


FIG. 105.

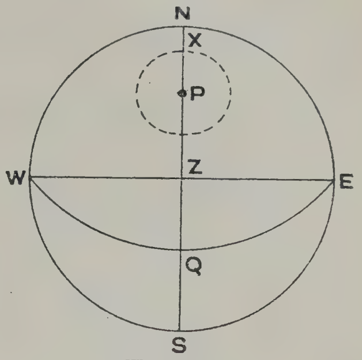


FIG. 106.

A body is said to be circumpolar when its parallel of declination does not intersect the horizon. In such a case the altitude of a body may be observed when on the meridian below pole.

Case 4. When a body passes the meridian below pole.

From Fig. 106 we have

$$\text{Lat.} = ZQ = 90° - PZ = PN = PX + XN = \text{Polar distance} + \text{altitude.}$$

It should be observed that *PN* is the altitude of the pole, so that the altitude of the pole at any place is equal to the latitude of that place.

Example (1):—On April 28th, 1914, in estimated position Lat. 30° 11′ S., Long. 84° 13′ E.; I.E., −1′ 10″; H.E., 50 ft.

The following observation was taken to determine the latitude of the ship:—

Obs. Meridian altitude sun's L.L. 45° 50′ 10″ (Azimuth North).

S.A.T. -	$24^h\ 00^m$ Apr. 27th.	Obs. alt. $\underline{\odot}$	45° 50′ 10″	Dec. -	13° 54′ N.
Long. -	5 37 (E.)	I.E.	−1 10	Eq. T. -	$2^m\ 26^s$ − to A.T.
G.A.T.	18 23		45 49·0		
Eq. T. -	− 2	Cor. - -	+ 8·1		
G.D. -	18 21 Apr. 27th.		45 57·1		
		ZX -	44 02·9		
		QX -	13 54·0		
		ZQ -	30 8·9 S.		

Lat. 30° 08′·9 S.

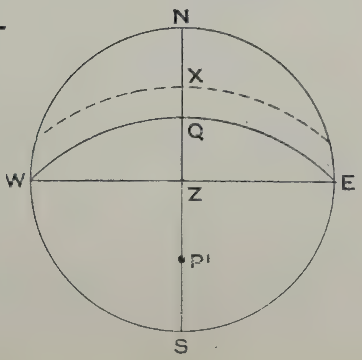


FIG. 107.

Example (2) :—On March 7th, 1914, in estimated position Lat. 55° 26′ N., Long. 50° 18′ W. ; I.E., – 1′ 10″; H.E., 50 ft.

The following observation was taken to determine the latitude of the ship :—

Obs. Meridian altitude moon's L.L. 60° 17′ 30″ (Azimuth South).

Time of Moon's mer. pass. at Greenwich -	8^h 22^m	Mar. 7th.
Cor. for Long.	+ 8	
S.M.T. - -	8 30	
Long. - -	3 21	(W.)
G.D. - -	11 51	Mar. 7th.

		Dec.
Obs. Alt. ☾ -	60° 17′ 30″	26° 12′·8 N.
I.E.	– 1 10	+ 1·0
	60 16·3	26 13·8 N.
Cor.	– 7·6	
	60 08·7	S.D.
S.D.	+ 16·1	15′ 44″
		+ 8 Cor.
	60 24·8	
Par.	+ 28·6	15 52
		+ 15 Aug.
	60 53·4	
		16 07
ZX	29 06·6	
QX	26 13·8	
		Hor. Par.
ZQ	55 20·4	57′ 38″
		+ 28 Cor.
		58 06

Lat. 55° 20′·4 N.

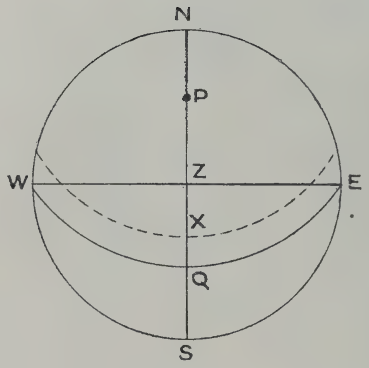


Fig. 108.

Example (3) :—On March 11th, 1914, in estimated position Lat. 54° 15′ N., Long. 45° 08′ W. ; I.E., – 1′ 10″ ; H.E., 50 ft.

The following observation was taken to determine the latitude of the ship :—

Obs. Meridian altitude Betelguese 43° 13′ 30″ (Azimuth South).

Obs. alt. Betelguese	43° 13′ 30″
I.E.	−1 10
	43 12·3
Cor.	−8·0
	43 04·3
ZX	46 55·7
QX	7 23·6
ZQ	54 19·3

Dec. 7° 23′·6 N.

Lat. 54° 19′·3 N.

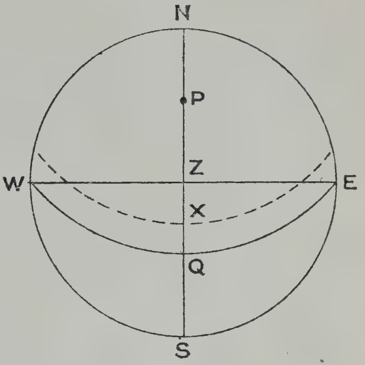


Fig. 109.

Example (4):—On April 21st, 1914, in estimated position Lat. 52° 55′ N., Long. 19° 14′ W.; I.E., – 1′ 30″; H.E., 50 ft.

The following observation was taken to determine the latitude of the ship:—

Obs. Meridian altitude Dubhe (below pole) 25° 13′ 30″ (Azimuth North).

Obs. alt. Dubhe	25° 13′ 30″
I.E.	−1 30
	25 12·0
Cor.	−9·0
XN	25 03·0
PX	27 47·1
PN	52 50·1

Dec. - - -	62° 12′·9 N.
	90 00
Polar distance	27 47·1

Lat. 52° 50′·1 N.

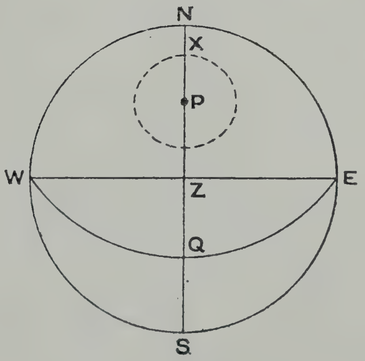


Fig. 110.

127. Maximum and minimum altitudes.—If an observer is at rest on the earth's surface, a heavenly body appears to rise before it passes the meridian, then to remain at rest for a brief interval, and then it appears to fall or "dip";

the converse takes place when the body passes the meridian below pole. The altitude of the body when it appears to be at rest (neither rising nor falling) is the meridian altitude of the body.

If the observer is in motion on any course other than East or West (true) he will be either approaching the body or receding from it; if he is approaching the body its altitude due to his motion is increasing, and if he is receding from it its altitude is decreasing. Now the body will appear to be at rest when its rate of change of altitude, due to the earth's rotation, is equal and opposite to its rate of change of altitude, due to the observer's motion; therefore, if the observer is approaching the body, it will appear to be at rest when its true altitude is diminishing, that is after its meridian passage, and in the case of a passage below pole before its meridian passage. If the observer is receding from the body it will appear to be at rest when its true altitude is increasing, that is before its meridian passage, and in the case of a passage below pole, after its meridian passage.

The altitudes of a body when, in such circumstances, it appears to be at rest above or below pole, are the maximum and minimum altitudes respectively. Thus we see that, unless the ship is steaming East or West (true), the maximum (or minimum) altitude of a body is not the meridian altitude; and, for this reason, when it is desired to take the meridian altitude, the time of the meridian passage should be worked out beforehand as explained above (§ 125), and the altitude observed at that time. The fact that this time has to be worked out with the estimated longitude causes no appreciable error unless the body passes very near the zenith.

128. Position line by ex-meridian altitude.—In Fig. 111, let the meridian of the estimated position *E* cut the circle of position in *A*, then, if the observation had been taken when the body was close to the meridian, the latitude of *A* can be simply found, and thus we immediately have the latitude and longitude of a point through which the position line may be drawn.

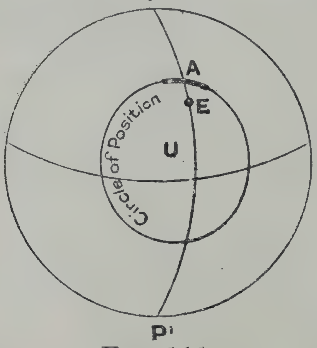


Fig. 111.

If the maximum or minimum altitude is observed, the time should be noted and the position line obtained as explained in this article.

In Fig. 112, which is on the plane of the horizon, let Z be the zenith of A, and X the true place of a heavenly body when near the celestial meridian of A. The zenith distance of X, ZB, when on the meridian, is less than ZX by a small quantity which may be denoted by y, so that, if z is the true zenith distance ZX, the meridian zenith distance ZB is $z - y = PB - PZ = p \sim c$ where p is the polar distance of the body, and c the co-latitude of the point A.

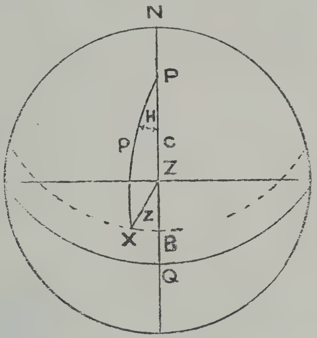


FIG. 112.

In the astronomical triangle PZX

$$\cos H = \frac{\cos z - \cos p \cos c}{\sin p \sin c},$$

$$\therefore \cos H = \frac{\cos (p \sim c + y) - \cos p \cos c}{\sin p \sin c}.$$

Subtracting each side from 1, we have

$$2 \text{ hav } H = \frac{\cos (p \sim c) - \cos (p \sim c + y)}{\sin p \sin c},$$

$$\therefore 2 \sin p \sin c \text{ hav } H$$
$$= \cos (p \sim c) - \cos (p \sim c) \cos y + \sin (p \sim c) \sin y,$$
$$= 2 \cos (p \sim c) \text{ hav } y + \sin (p \sim c) \sin y,$$

$$\therefore \sin y = \frac{2 \sin p \sin c \text{ hav } H}{\sin (p \sim c)} - 2 \cot (p \sim c) \text{ hav } y.$$

Now let

$$\sin y_1 = \frac{2 \sin p \sin c \text{ hav } H}{\sin (p \sim c)}.$$

and

$$\sin y_2 = 2 \cot (p \sim c) \text{ hav } y,$$

in which $(p \sim c)$ may be regarded as equal to z, and y as equal to y_1; then, since y_1 and y_2 are small angles,

$$y = y_1 - y_2$$

where $\sin y_1 = \dfrac{2 \cos L \cos D \text{ hav } H}{\sin (L \mp D)}$

and $\sin y_2 = 2 \tan \text{(altitude) hav } y_1$,

the signs $\sim$ or $+$ being used according as L and D are of the same or of different names.

The values of y_1 and y_2 may be found from Inman's Tables; Ex-Meridian Tables I., II., and III. give the value of y_1 and Table IV. gives the value of y_2.

When y has been found it should be added to the true altitude; the meridian altitude thus obtained, when combined with the declination in the manner previously explained (§ 126), gives the latitude of the point through which the position line may be drawn. Therefore the position line is drawn on the chart through the point A, whose latitude is the latitude thus found and whose longitude is the estimated longitude, and in a direction at right angles to the azimuth of the body.

When the heavenly body is near the meridian below pole the formulæ above are the same except that instead of H we have $12^h - H$. In this case the altitude is decreasing as the body approaches the meridian, so that the correction y is subtractive from the true altitude.

The limits within which an observation may be worked by the ex-meridian method are defined by the scope of the tables. When an observation is taken of a heavenly body which is near the meridian, and it is found that it is impossible to work it out by means of the ex-meridian tables, it should be worked in the ordinary manner which has been described in the previous chapters.

Example (1):—On March 2nd, 1914, at about $11^h\ 30^m$ A.M. (S.M.T. nearly), in estimated position Lat. 49° 17′ N., Long. 38° 15′ W., the deck watch was slow on G.M.T. $2^h\ 15^m\ 10^s$ I.E., + 1′ 40″; H.E., 40 ft.

The following observation was taken:—

Deck watch, $11^h\ 48^m\ 53^s$. Obs. alt. $\underline{\odot}$ 32° 24′ 40″.

Required the latitude of the point through which to draw the position line.

S.M.T.	$23^h\ 30^m$ Mar. 1st.	Obs. alt. $\underline{\odot}$	32° 24′ 40″		
Long. -	2 33 (W.)	I.E. -	+ 1 40	Dec.	7° 23′·0 S.
				Eq.T.	$12^m\ 25^s$·8 + to A.T.
G.D. -	2 03 Mar. 2nd.		32 26·3	Tab. I. -	- 9·890
		Cor. -	+ 8·6	Tab. II. -	- 7·909
D.W. -	$11^h\ 48^m\ 53^s$	True alt. -	32 34·9		7·799
Slow -	2 15 10	y - -	+ 43·1	Tab. III. -	- 43′·3
				Tab. IV. -	- —·2
	14 04 03	Mer. alt. -	33 18·0		
	12 00 00		90 00	y - - -	= 43·1
G.M.T. -	2 04 03	M.Z.D. -	56 42·0		
Long. -	2 33 00(W.)	Dec. -	7 23·0		
M.T.P. -	23 31 03	Lat. -	49 19·0 N.		
Eq. T.	— 12 26				
H. -	23 18 37	Azimuth from Tables	- S. 12½° E.		

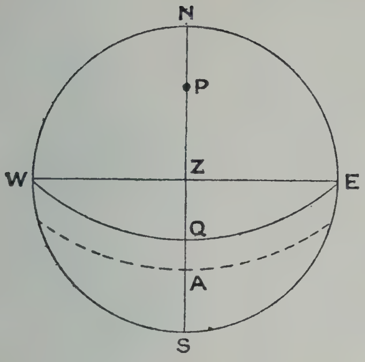


FIG. 113.

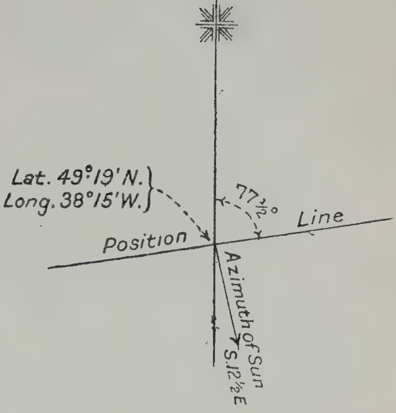


FIG. 114.

Therefore, the position line is drawn through the point whose position is Lat. 49° 19′ N., Long. 38° 15′ W. and in a direction $\begin{smallmatrix}\text{N.}\\\text{S.}\end{smallmatrix}\ 77\frac{1}{2}^{\circ}\ \begin{smallmatrix}\text{E.}\\\text{W.}\end{smallmatrix}$, as shown in Fig. 114.

Example (2).:—On March 28th, 1914, at about 4^h 20^m A.M. (S.M.T. nearly), in estimated position Lat. 56° 51′ N., Long. 17° 25′ W., the deck watch was slow on G.M.T. 3^h 47^m 19^s, I.E., – 1′ 50″ ; H.E., 40 ft.

The following observation was taken :—

Deck watch 1^h 43^m 47^s. Obs. alt. Capella (below pole) 13° 02′ 40″.

Required the latitude of the point through which to draw the position line.

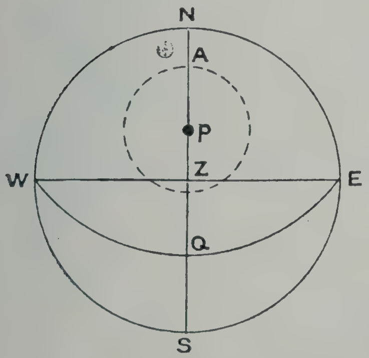


FIG. 115.

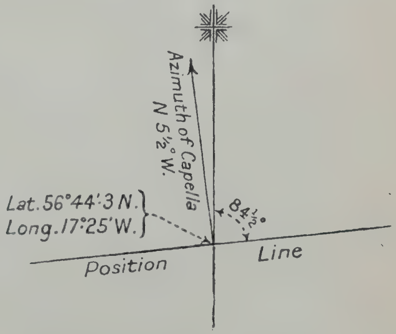


FIG. 116.

S.M.T.	16^h	20^m		Mar. 27th.
Long.	1	09	40^s	(W.)
G.D.	17	30		Mar. 27th.
D.W. -	1^h	43^m	47^s	
Slow -	3	47	19	
	5	31	06	
	12	00	00	
G.M.T. -	17	31	06	
Long. -	1	09	40	(W.)
M.T.P. -	16	21	26	
R.A.M.S.	0	18	55·1	+
For 1^h			+9·9	
,, 30^m			+4·9	
,, 1^m			+ ·2	
R.A.M. -	16	40	36·1	
R.A. -	5	10	21	—
H. - -	11	30	15·1	
	12	00	00	
$12^h - H.$	0	29	44·9	

Obs. alt. -	13° 02′ 40″
I.E. - -	−1 50
	13 00·8
Cor. - -	−10·3
True alt. -	12 50·5
y - -	−11·3
Mer. alt. -	12 39·2
Polar dist.	44 05·0
Lat. -	56 44·2 N.
Azimuth - N. 5½° W. from Tables.	

R.A.	5^h 10^m 21^s
Dec. -	45° 55′ N.
	90 00
Polar dist.	44 05
Tab. I. -	9·591
Tab. II.	7·624
	7·215
Tab. III.	11′·3
Tab. IV.	−0·0
y	=11·3

Therefore, the position line is drawn through the point whose position is Lat. 56° 44′·3 N., Long. 17° 25′ W., and in a direction $\begin{matrix}\text{N.}\\\text{S.}\end{matrix}\ \overset{\circ}{84}\tfrac{1}{2}\ \begin{matrix}\text{E.}\\\text{W.}\end{matrix}$, as shown in Fig. 116.

129. Position line by altitude of Polaris.—In Fig. 117 let *U* be the geographical position of Polaris, and *PP′* the meridian of the estimated position *E*. Let *PP′* intersect the circle of position in *A*, then if we can obtain the latitude of the point *A*, the position line may be drawn at right angles to the azimuth of Polaris through the point whose latitude is the latitude of *A*, and whose longitude is that of the estimated position.

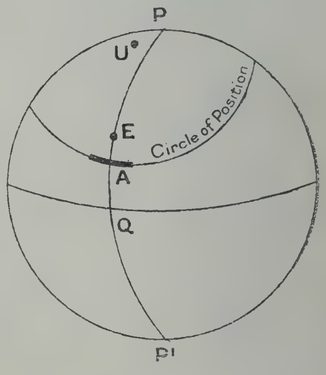


Fig. 117.

In Fig. 118 let Z be the zenith of the point A, and X the true place of Polaris, whose hour angle is H and whose altitude is a.

As the polar distance of Polaris is now about $70'$, and as the latitude of the place is the altitude at that place of the pole (§ 126), it follows that the altitude of this star cannot differ from the latitude by more than $70'$. Therefore, by applying a small correction to the altitude the latitude of A (Fig. 117) may be obtained.

Since the latitude PN differs very little from the altitude, we may assume that $PN = a - y$ where y is the correction to be found.

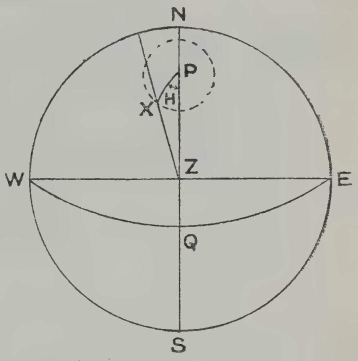


FIG. 118.

In the triangle PZX,

$$\cos H = \frac{\cos ZX - \cos PZ \cos PX}{\sin PZ \sin PX};$$

therefore

$$\cos H = \frac{\sin a - \sin (a - y) \cos p}{\cos (a - y) \sin p};$$

therefore

$$\cos H (\cos a \cos y \sin p + \sin a \sin y \sin p)$$
$$= \sin a - \sin a \cos y \cos p + \cos a \sin y \cos p.$$

Since y and p are not greater than $70'$, we may put

$$\sin p = p, \quad \cos p = 1 - \frac{p^2}{2}, \quad \sin y = y, \text{ and } \cos y = 1 - \frac{y^2}{2},$$

and we have, neglecting small quantities of the third order,

$$\cos H (p \cos a + py \sin a) = \sin a - \sin a \left(1 - \frac{p^2 + y^2}{2}\right) + y \cos a;$$

therefore

$$y = p \cos H + py \cos H \tan a - \left(\frac{p^2 + y^2}{2}\right) \tan a.$$

Neglecting terms of the second order on the right-hand side, we have, as a first approximation, $y = p \cos H$.

Substituting this value on the right, we have

$$y = p \cos H + \tan a \left[p^2 \cos^2 H - \frac{p^2}{2} - \frac{p^2 \cos^2 H}{2}\right]$$
$$= p \cos H - \tfrac{1}{2} p^2 \sin^2 H \tan a.$$

Therefore, if y and p are expressed in seconds of arc,

$$y'' = p'' \cos H - \tfrac{1}{2} \sin 1'' (p \sin H)^2 \tan a.$$

Now $H = \text{R.A.M.} - \text{R.A.}\ast$.

Therefore

$$\begin{aligned}\text{Lat.} &= a - y\\ &= a - p\cos(\text{R.A.M.} - \text{R.A.}\ast) + \tfrac{1}{2}\sin 1''\,[p\sin(\text{R.A.M.} - \text{R.A.}\ast)]^2\tan a.\end{aligned}$$

The second and third terms on the right are tabulated in the Nautical Almanac for constant values of p and R.A.✱; Table I. gives the value of $p\cos(\text{R.A.M.} - \text{R.A.}\ast)$ and Table II. the value of $\tfrac{1}{2}\sin 1''\,[p\sin(\text{R.A.M.} - \text{R.A.}\ast)]^2\tan a$.

Table III. gives a correction for the change of the declination and right ascension during the year, increased by 1′. The actual correction is sometimes positive and sometimes negative, therefore if 1′ is always subtracted from the altitude the numbers given in Table III. are always additive.

It will be noticed that the elements in the Nautical Almanac are tabulated for local sidereal time, but, as explained in § 96, this is the same as the right ascension of the meridian.

The azimuth of Polaris is tabulated in Inman's Tables for various latitudes and right ascensions of the meridian.

Example:—On March 14th, 1914, at about $6^h\ 30^m$ P.M. (S.M.T. nearly), in estimated position Lat. 29° 42′ N., Long. 126° 30′ E., the deck watch was slow on G.M.T. $5^h\ 06^m\ 47^s$ I.E., + 1′ 30″; H.E., 30 ft.

The following observation was taken:—

Deck watch, $4^h\ 57^m\ 05^s$; obs. alt. Polaris, 30° 18′ 40″.

Required the position line.

S.M.T. -	6^h	30^m	Mar. 14th
Long. -	8	26	(E.)
G.D. -	22	04	Mar. 13th
D.W. -	4^h	57^m	05^s
Slow -	5	06	47
	10	03	52
	12	00	00
G.M.T. -	22	03	52
Long. -	8	26	00 (E.)
M.T.P. -	6	29	52
R.A.M.S. -	23	24	42·5 +
For 4^m -			+ 0·7
	29	54	35·2
	24	00	00
R.A.M. -	5	54	35·2

Obs. alt. -	30°	18′	40″
I.E. - -		+1	30
	30	20·2	
Cor. - -		−7·1	
True alt. -	30	13·1	
Subtract -		−1·0	
	30	12·1	
1st cor. - -		−27·4	
	29	44·7	
2nd cor. -		+0·3	
3rd cor. -		+1·2	
Lat. - -	29	46·2 N.	

From Inman's Tables the azimuth of Polaris is found to be N. 1½° W.; therefore the position line is drawn on the chart through the point whose position is Lat. 29° 46′·2 N., Long. 126′ 30° E., and in a direction $\begin{smallmatrix}\text{N.}\\\text{S.}\end{smallmatrix}\, 88\tfrac{1}{2}{}^{\circ} \begin{smallmatrix}\text{E.}\\\text{W.}\end{smallmatrix}$

130. Position line by "Longitude by chronometer" method.—This problem consists of finding the longitude of one of the points where the estimated parallel of latitude intersects the circle of position.

In Fig. 119 let the parallel of latitude *AB* intersect the circle of position in *A* and *B*, and let the body be West of the observer's meridian at the time of observation. Then, if we can find the longitude of *A*, the position line can be drawn on the chart through the point the longitude of which has been found, and the latitude of which is the estimated latitude used in the calculation.

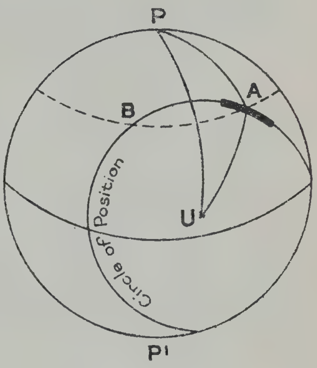


Fig. 119.

$$\text{Now longitude} = \text{M.T.P.} \sim \text{G.M.T.}$$
$$= [H + \text{R.A.}\ast - \text{R.A.M.S.}] \sim \text{G.M.T.},$$

or in the case of the sun,

$$\text{Long.} = [H \pm \text{Eq. T.}] \sim \text{G.M.T.}$$

In each case the only unknown quantity on the right-hand side of the equation is the hour angle of the body, so that, to find the longitude of *A*, we have first to calculate the hour angle of the body.

In the triangle *PZX*, Fig. 102—

$$\text{hav}\, ZPX = \text{cosec}\, PZ \,\text{cosec}\, PX \sqrt{\text{hav}\,[ZX + (PX \sim PZ)]\,\text{hav}\,[ZX \sim (PX \sim PZ)]}.$$

Now $PZ = 90° - L$ and $PX = 90° \pm D$; therefore

$$\text{hav}\, H = \sec L \sec D \sqrt{\text{hav}\,[z + (L \mp D)]\,\text{hav}\,[z \sim (L \mp D)]},$$

the sign $\mp$ being taken in the usual manner.

When looking out the hour angle from the haversine table it should be borne in mind that, if the body is West of the meridian, the hour angle is less than 12 hours, and if East of the meridian, the hour angle is greater than 12 hours.

Having found the hour angle, the longitude of *A* may be obtained from the formula given above. The position line is drawn on the chart through the point whose latitude is the latitude of the estimated position, and whose longitude is the longitude thus found; its direction is at right angles to the azimuth of the body.

Example (1):—On March 3rd, 1914, at about $4^h\ 30^m$ P.M. (S.M.T. nearly) in estimated position Lat. 30° 21′ N., Long. 160° 25′ E., the deck watch was slow on G.M.T. $3^h\ 11^m\ 21^s$. I.E., + 1′ 20″; H.E., 30 ft. The following observations were taken:—

Deck watch	$2^h\ 33^m\ 52^s$	Obs. alt. $\underline{\odot}$	18° 27′ 30″
,, ,,	2 34 20	,, ,, ,,	18 18 50
,, ,,	2 34 41	,, ,, ,,	18 12 30

Required the longitude of the point through which to draw the position line.

$2^h\ 33^m\ 53^s$	18° 27′ 30″
2 34 20	18 18 50
2 34 41	18 12 30
3/102 54	3/ 58 50
2 34 18	18 19 37

S.M.T.	$4^h 30^m$ Mar. 3rd.	Obs. alt. $\underline{\odot}$	18° 19′ 37″	Dec.	7° 07′·9 S.
Long.	10 41 40^s (E.)	I.E.	+1 20	Eq. T.	$12^m 17^s$·7 + to A.T.
G.D.	17 48 Mar. 2nd.		18 21·0		
		Cor.	+8·0		
D.W.	$2^h 34^m 18^s$				
Slow	3 11 21	True alt.	18 29·0		
	5 45 39	True *z*.	71 31·0		
	12 00 00				
G.M.T.	17 45 39				
L	30°21′·0 N.	*L.* sec	0·06401		
D	7 07·9 S.	*L.* sec	0·00337		
(*L*+*D*)	37 28·9				
z	71 31·0				
z+(*L*+*D*)	108 59·9	½ *L.* hav	4·91069		
z ~ (*L*+*D*)	34 02·1	½ *L.* hav	4·46637		
		L. hav *H*	9·44444	*H*	$4^h 14^m 42^s$
				Eq.T.	12 17·7
				M.T.P.	4 26 59·7
				G.M.T.	17 45 39
				Long.	10 41 20·7 (E.)
				,,	160° 20′·2 E.

Azimuth N. 110° W.
from Tables.

Therefore the position line is drawn through the point whose position is Lat. 30° 21′ N., Long. 160° 20′·2 E., and it runs $\begin{matrix}\text{N.}\\ \text{S.}\end{matrix}$ 20° $\begin{matrix}\text{W.}\\ \text{E.}\end{matrix}$.

If two observations are taken and two position lines found, the position of the ship may be obtained by plotting the position lines.

If the azimuth of the body is 90°, that is, if the body is on the prime vertical, the position line runs North and South and is coincident with the meridian the longitude of which has been obtained from the observation; in such a case it is obvious that the longitude obtained is the longitude of the ship, irrespective of the latitude used in the calculation.

When the latitude of the ship is known at the time of the observation the longitude obtained is the longitude of the ship; therefore when an altitude of a body on the meridian can be taken simultaneously, or nearly simultaneously, with that of a body whose azimuth is not less than 30°, the position of the ship can be immediately obtained from the observations, without the necessity of plotting the position lines or having recourse to the traverse table; this is illustrated by the following example.

Example (2):—On March 28th, 1914, at about $7^h\ 15^m$ P.M. (S.M.T. nearly), in estimated position Lat. 42° 41′ N., Long. 40° 20′ W., the deck watch was slow on G.M.T. $3^h\ 39^m\ 15^s$. I.E., − 1′ 30″; H.E., 45 ft.

The following observations were taken to determine the position of the ship:—

Obs. meridian altitude Procyon 52° 48′ 30″ (Azimuth South) Deck watch $6^h\ 16^m\ 08^s$. Obs. alt. Regulus (E.) 46° 02′ 00″.

Obs. alt. Procyon	52° 48′ 30″
I.E. - - - -	−1 30
	52 47·0
Cor. - - -	− 7·4
	52 39·6
ZX - - -	37 20·4
QX - - -	5 26·7
ZQ - - -	42 47·1
Latitude -	42° 47′·1 N.

Dec. 5° 26′·7 N.

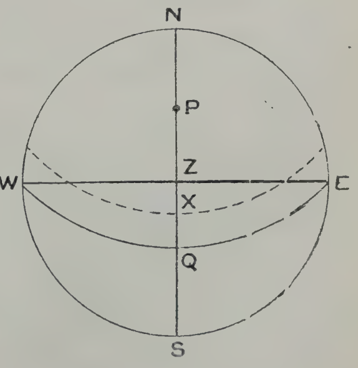


Fig. 120.

S.M.T.	$7^h 15^m$	Mar. 28th.
Long.	2 41 20^s (W.)	
G.D.	9 56	Mar. 28th.
D.W.	$6^h 16^m 08^s$	
Slow	3 39 15	
G.M.T.	9 55 23	

Obs. alt. Regulus	46° 02′ 00″
I.E. -	—1 30
	46 00·5
Cor. -	—7·6
	45 52·9
True *z* -	44 07·1

R.A.	$10^h 03^m 49^s{\cdot}8$
Dec.	12° 23′·2 N.
R.A.M.S.	$0^h\ 21^m\ 32^s{\cdot}9$
For 1^h	9·9
,, 50^m	8·2
,, 5^m	·8
	0 21 51·8

L	42° 47′·1 N.
D	12 23·2 N.
(*L* — *D*)	30 23·9
z	44 07·1
z + (*L*—*D*)	74 31·0
z — (*L*—*D*)	13 43·2

L sec	·13436
L sec	·01023
½ *L* hav	4·78205
½ *L* hav	4·07718
L hav *H*	9·00382

H	$21^h 31^m 51^s$
R.A.✳	10 03 49·8
	31 35 40·8
	24 00 00
R.A.M.	7 35 40·8
R.A.M.S.	0 21 51·8
S.M.T.	7 13 49
G.M.T.	9 55 23
Long.	2 41 34 (W.)
,,	40° 23′·5 W.

Position of ship: Lat. 42° 47′·1 N., Long. 40° 23′·5 W.

131. Longitude by equal altitudes.—The following method of finding the longitude, although not strictly belonging to the theory of position lines, is given on account of the extreme brevity of the calculations involved.

Suppose that the times, shown by the chronometer, when a heavenly body has the same altitude before and after its meridian passage, are t_1 and t_2 respectively; then, if we neglect the motion of the ship and the change in the declination of the body, the meridian passage of the body takes place when the chronometer shows $\frac{t_1 + t_2}{2}$. Therefore the G.M.T. of the meridian passage is known, and this, compared with the S.M.T. of passage, obtained as shown in § 125, gives the longitude of the ship.

When we take into consideration the motion of the ship and the change in the declination of the body, the body may be assumed to be at its maximum altitude (§ 127) at the mean of the chronometer times, provided that the altitudes are taken within 30 minutes of the time of the meridian passage. If, therefore, we can find the interval between the times of meridian passage and maximum altitude, this interval applied to the mean of the chronometer times will give the chronometer time of the meridian passage, and hence, as explained above, the longitude of the ship.

In Fig. 121, let Z be the zenith of the ship and X the true place of a heavenly body when at its maximum altitude.

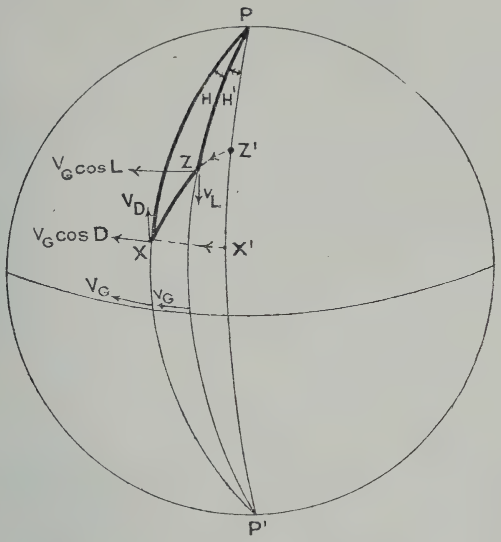


Fig. 121.

Let the velocities of the ship in latitude and longitude be v_L and v_G respectively, so that the velocity of Z in a direction perpendicular to the meridian is v^G cos L, where L is the latitude of the ship.

Let the velocities of X in declination and hour angle be V_D and V_G respectively.

When the body is at its maximum altitude, the relative velocity of its true place X, along the circle of altitude XZ, is zero. Therefore

$$V_G \cos D \sin PXZ - V_D \cos PXZ - v_G \cos L \sin PZX$$
$$+ v_L \cos PZX = 0.$$

Since the angles PXZ and PZX are small, we may put cos $PXZ = 1$, and cos $PZX = -1$.

Also

$$\sin PXZ = \frac{\sin H \cos L}{\sin z} \text{ and } \sin PZX = \frac{\sin H \cos D}{\sin z}.$$

$$\therefore \frac{V_G \cos D \cos L}{\sin z} \sin H - V_D - \frac{v_G \cos L \cos D}{\sin z} \sin H - v_L = 0.$$

$$\therefore \sin H = \frac{\sin z\,(v_L + V_D)}{\cos L \cos D\,(V_G - v_G)}.$$

Since X is very near the meridian we may substitute $(L \sim D)$ for z, and since H is a small angle we may write $H^s \sin 1^s$ for sin H, and the equation becomes

$$H = (\tan L \sim \tan \mathrm{D}) \frac{v_L + V_D}{V_G - v_G} \operatorname{cosec} 1^{\mathrm{s}}.$$

Now let Z' be the zenith of the ship when the body is on the ship's meridian, and let H' be the angle $Z'PZ$; then, since the body traces out the angle $H' + H$ at speed V_G in the same time as the ship traces out the angle H' at speed v_G, we have

$$\frac{H' + H}{H'} = \frac{V_G}{v_G}$$

$$\therefore H' = \frac{v_G}{V_G - v_G} H$$

$$\therefore H' + H = \frac{V_G}{V_G - v_G} H$$

Therefore the interval between the times of the meridian passage and the maximum altitude is given in seconds of time by

$$H' + H = (\tan L \sim \tan D) \frac{(v_L + V_D) V_G \operatorname{cosec} 1^s.}{(V_G - v_G)^2}$$

$$= (\tan L \sim \tan D) \frac{(v_L + V_D)\ V_G^{-1} \operatorname{cosec} 1^s.}{\left(1 - \frac{v_G}{V_G}\right)^2}$$

$$= (\tan L \sim \tan D)\ (v_L + V_D)\ V_G^{-1} \left(1 + \frac{2\,v_G}{V}\right) \operatorname{cosec}\ 1^s.$$

In the case of the sun, the velocity in longitude is approximately the same as that of the mean sun, which is 900 knots, and substituting this value for V_G the expression for the interval becomes

$$15{\cdot}28\ (\tan L \sim \tan D)\ (v_L + V_D)\ (1 + {\cdot}002\ v_G).$$

If the latitude and declination are of opposite names the first expression within brackets becomes $(\tan L + \tan D)$.

If the sun and ship are moving in latitude in the same direction—that is, both North or both South—the second expression within brackets becomes $(v_L \sim V_D)$.

If the ship's course is in an Easterly direction the third expression within brackets becomes $(1 - {\cdot}002\ v_G)$.

The general expression for the interval may therefore be written

$$15{\cdot}28\ (\tan L \overset{\sim}{+} \tan D)\ (v_L \overset{\sim}{+} V_D)\ (1 \pm {\cdot}002\ v_G).$$

Although the velocities in longitude of the stars and planets differ from that of the sun, the difference is so small that the formula is still applicable when these bodies are observed. The moon should not be used for finding longitude by this method.

It should be remembered that the maximum altitude occurs before or after the meridian passage according as the body and ship are parting or closing. The rule for applying the interval to the G.M.T. of maximum altitude is;—mark the interval *plus* when the ship and sun are *parting*.

It is important, when employing this method, that the body should be moving sufficiently fast in altitude for the times to be exactly noted; this will be the case if the azimuth is not less than 20°.

The height of eye should be the same at both observations, and, if possible, the same sextant shades should be used.

The value of this method of finding longitude lies in the fact that a very brief interval elapses between the observations, and consequently the refraction is probably the same at both altitudes; moreover, the error due to error in the reckoning is not so directly involved as when a position line has to be transferred for the run of the ship. If a meridian altitude or an ex-meridian altitude is observed between the observations the position of the ship is obtained. The method is particularly valuable in very low latitudes where the sun, when near the meridian, is nearly always suitable for observation.

The following table has been calculated to give the value of $15{\cdot}28 \tan x$ where x varies from 0° to 46° 51′.

TABLE TO FACILITATE FINDING LONGITUDE FROM EQUAL ALTITUDES.

L or *D*	—	*L* or *D*	—	*L* or *D*	—	*L* or *D*	—
0° 00′	0·0	15° 01′	4·1	28° 13′	8·2	38° 50′	12·3
0 23	0·1	15 22	4·2	28 31	8·3	39 04	12·4
0 45	0·2	15 43	4·3	28 48	8·4	39 17	12·5
1 07	0·3	16 04	4·4	29 05	8·5	39 31	12·6
1 30	0·4	16 25	4·5	29 22	8·6	39 44	12·7
1 52	0·5	16 45	4·6	29 39	8·7	39 57	12·8
2 15	0·6	17 06	4·7	29 56	8·8	40 10	12·9
2 37	0·7	17 26	4·8	30 13	8·9	40 23	13·0
3 00	0·8	17 47	4·9	30 30	9·0	40 36	13·1
3 22	0·9	18 07	5·0	30 47	9·1	40 49	13·2
3 45	1·0	18 27	5·1	31 03	9·2	41 02	13·3
4 07	1·1	18 48	5·2	31 20	9·3	41 15	13·4
4 29	1·2	19 08	5·3	31 36	9·4	41 28	13·5
4 52	1·3	19 28	5·4	31 52	9·5	41 40	13·6
5 14	1·4	19 48	5·5	32 08	9·6	41 53	13·7
5 36	1·5	20 08	5·6	32 24	9·7	42 05	13·8
5 59	1·6	20 27	5·7	32 40	9·8	42 18	13·9
6 21	1·7	20 47	5·8	32 56	9·9	42 30	14·0
6 43	1·8	21 07	5·9	33 12	10·0	42 42	14·1
7 05	1·9	21 26	6·0	33 28	10·1	42 54	14·2
7 27	2·0	21 46	6·1	33 44	10·2	43 06	14·3
7 49	2·1	22 05	6·2	33 59	10·3	43 18	14·4
8 12	2·2	22 24	6·3	34 14	10·4	43 30	14·5
8 34	2·3	22 44	6·4	34 30	10·5	43 42	14·6
8 56	2·4	23 03	6·5	34 45	10·6	43 54	14·7
9 17	2·5	23 22	6·6	35 00	10·7	44 05	14·8
9 39	2·6	23 41	6·7	35 15	10·8	44 17	14·9
10 01	2·7	23 59	6·8	35 30	10·9	44 28	15·0
10 23	2·8	24 18	6·9	35 45	11·0	44 40	15·1
10 45	2·9	24 37	7·0	36 00	11·1	44 51	15·2
11 06	3·0	24 55	7·1	36 15	11·2	45 02	15·3
11 28	3·1	25 14	7·2	36 29	11·3	45 13	15·4
11 50	3·2	25 32	7·3	36 44	11·4	45 25	15·5
12 11	3·3	25 51	7·4	36 58	11·5	45 36	15·6
12 33	3·4	26 09	7·5	37 12	11·6	45 47	15·7
12 54	3·5	26 27	7·6	37 26	11·7	45 58	15·8
13 15	3·6	26 45	7·7	37 41	11·8	46 08	15·9
13 37	3·7	27 03	7·8	37 55	11·9	46 19	16·0
13 58	3·8	27 20	7·9	38 09	12 0	46 30	16·1
14 19	3·9	27 38	8·0	38 23	12·1	46 41	16·2
14 40	4·0	27 56	8·1	38 36	12·2	46 51	16·3

To use the table, take out the numbers corresponding to the latitude and declination; add these numbers together when L and D are of different names, and take their difference when L and D are of the same name. Multiply the result by the relative speed of the ship and body in latitude. This gives the interval, disregarding the motion of the ship in longitude. To correct the interval for this motion, multiply it by ·002 times the speed of the ship in longitude and apply it to the interval just found ± according as the ship's course is a Westerly or an Easterly one.

The following examples show how the longitude is obtained by aid of this table.

Example (1):—On March 2nd, 1914, in estimated position Lat. 2° 10′ N., Long. 71° 15′ E., the deck watch was slow on G.M.T. $0^h\ 56^m\ 38^s$, and the ship was steaming N. 35° W. (true) at 18 knots.

The following observations were taken to determine the longitude of the ship.

The sun had equal altitudes at the following times by deck watch:—

	(A.M.) $6^h\ 04^m\ 58^s$.			(P.M.) $6^h\ 55^m\ 01^s$.
S.A.T.	$24^h\ 00^m$	Mar. 1st.	Dec.	7° 29′·2 S.
Long.	4 45	(E.)	Eq. T.	$12^m\ 29^s$ + to A.T.
G.A.T.	19 15	Mar. 1st.		
Eq. T.	+ 12			
G.D.	19 27	Mar. 1st.		

N. 35° W. 18′ ≡ *d* Lat. 14′·74 N., Dep. 10′·32 W., *d* Long. 10′·32 W.

Speed in latitude - - - -	14·74 knots (N.)
Speed in declination - - -	·95 knots (N.)
Relative speed - - - -	13·79 knots (parting).

$$\left.\begin{array}{lll} \text{From table} & 2^\circ\ 10'\ \text{N. gives} & 0{\cdot}6 \\ \text{,,} \quad \text{,,} & 7^\circ\ 29'\ \text{S.} \quad \text{,,} & 2{\cdot}0 \end{array}\right\} \begin{array}{l} L \text{ and } D \text{ different} \\ \text{names:—add.} \end{array}$$

$$\underline{2{\cdot}6}$$

$$2{\cdot}6 \times 13{\cdot}79 = 35^s{\cdot}85.$$

Speed of ship in longitude is 10·32 knots (W.)

$$35{\cdot}85 \times {\cdot}002 \times 10{\cdot}32 = 0^s{\cdot}74.$$

$$\begin{array}{r} 35^s{\cdot}85 \\ {\cdot}74 \\ \hline \end{array}$$

Interval between times of max. and mer. alts. 36·59

D.W. (A.M.) - -	6h	04m	58s
D.W. (P.M.) - -	6	55	01
	2/12	59	59
Mean D.W. time -	6	29	59
	12	00	00
	18	29	59
Slow - - -	0	56	38
G.M.T. at Max. Alt.	19	26	37
Interval - -			+37
G.M.T. at Mer. Pass.	19	27	14
Eq. T. - - -		−12	29
G.A.T. at Mer. Pass.	19	14	45
S.A.T. at Mer. Pass.	24	00	00
Longitude - -	4	45	15 (E.)
	71°	18′·75 E.	

Example (2):—On April 27th, 1914, at about 7h 45m P.M. (S.M.T. nearly) in estimated position Lat. 19° 23′ N., Long. 7° 15′ W. the deck watch was slow on G.M.T., 3h 13m 27s and the ship was steaming S. 62° E. (true) at 15 knots.

The following observations were taken to determine the longitude of the ship.

Regulus had equal altitudes at the following times by deck watch.

(E. of Mer.) 4h 40m 20s. (W. of Mer.) 5h 18m 46s.

S.M.T.	7h	45m	Apl. 27th
Long.		29	(W.).
G.D.	8	14	Apl. 27th.

R.A.✱	10h	03m	50s
Dec.	12°	23′·2 N.	
R.A.M.S.	2h	19m	49s·5
For 10m			+ 1 ·6
,, 4m			+ ·7
	2	19	51 ·8

S. 62° E. 15′ ≡ *d* Lat. 7′·04 S., Dep. 13′·24 E., *d* Long. 14′ E.

Speed in latitude - - - 7·04 knots (S.).
Speed in declination - - - 0·00

Relative speed - - - - 7·04 knots (nearing).

From table 19° 23′ N. gives 5·4 } *L* and *D* same names :—
,, ,, 12° 23′ N. ,, 3·4 } subtract.

2·0

2·0 × 7·04 = 14s·08.

Speed of ship in longitude is 14 knots (E.).

$$14{\cdot}08 \times {\cdot}002 \times 14 = 0^s{\cdot}39.$$

	$14^s{\cdot}08$
	$-\,{\cdot}39$
Interval between times of Max. and Mer. Alts.	$13{\cdot}69$

R.A.✱	$10^h\,03^m\,50^s$	D.W. (E. of Mer.)	$4^h\,40^m\,20^s$
R.A.M.S.	2 19 52	D.W. (W. of Mer.)	5 18 46
S.M.T. of Mer. Pass	7 43 58		2/9 59 06
		Mean D.W. time -	4 59 33
		Slow - - - -	3 13 27
		G.M.T. of Max. Alt. -	8 13 00
		Interval - - -	−14
		G.M.T. of Mer. Pass. -	8 12 46
		S.M.T. of Mer. Pass. -	7 43 58
		Longitude - - -	0 28 48(W.)
			7° 12′ W.

132. Notes on observations for determining position lines.—The accuracy of all altitudes depends on the degree of exactness with which the position of the sea horizon is known, in other words on the dip, which, as explained in § 52, occasionally differs considerably from the tabulated values on account of abnormal refraction. In addition, the accuracy of an altitude depends on the distinctness with which the sea horizon can be seen by the observer.

When mist causes the horizon to appear indefinite, it is advisable to take an observation from a position where the height of eye is as low as possible, and so bring the sea horizon nearer to the observer (§ 57).

The difficulty caused by the sea horizon being obscured can be overcome approximately, when ships are in company, by using for shore horizon the water line of another ship which has the same bearing as the sun, care being taken to measure the distance of the ship by range-finder at the time of observation. As the dip of the shore horizon (§ 58) cannot be easily and accurately obtained from the tables it should be calculated from the formula, which, for convenience in this case, may be put in the form :—

$$\text{Dip (in minutes of arc)} = 1146\,\frac{h}{d} + {\cdot}0002\ d,$$

where h is the height of eye in feet and d the distance in yards.

The best time for taking observations for obtaining the position of the ship is when the stars first become visible or just before they disappear at evening and morning twilight respectively, as the horizon is usually very well defined at those times.

The altitudes of Venus and Jupiter may sometimes be observed in daylight when the bodies are near the meridian. In order to locate the body which it is wished to observe, it is advisable to previously calculate its approximate altitude and to set the altitude on the sextant. With the sextant telescope directed to the correct point of the horizon the body should be seen in the field of the telescope.

Observations should not be taken from positions where the ray of light from the body observed has to pass through hot air or steam.

When the heavenly body is not near the meridian three or five observations should be taken in quick succession and their mean used to work out the observation; this procedure should not be followed in the case of a body which is near the meridian, because in that position the altitude of the body does not vary directly as the time.

The minute hand of the deck watch should always be looked at by the observer immediately after taking the last observation, to see if the correct minute has been written down by the time taker. The time by the ship's clock should always be noted, and also the reading of the patent log or speed recorder.

It is as necessary for the time by the deck watch to be taken accurately as for the altitude to be correctly measured. The method of taking time by the deck watch is given in Chapter XVI.

When observing, give the time taker a warning of about 5 seconds and call 'top at the instant of making the contact.

The sextant telescope of the highest power that will give clear images of the body and the horizon should always be used.

When the body appears very bright the eye is strained and the exact instant of contact is difficult to detect; consequently the darkest sextant shade that will give a clear image of the body should be used.

The index error of the sextant should be determined just before observations are taken or just afterwards.

Whenever a star or planet is observed its compass bearing should be taken, to assist, if necessary, in determining the name of the body observed, as will be explained in Chapter XV.

It is always advisable to take observations of the sun in the late afternoon, even if it is intended to take observations of stars a little later on; the observations of the sun need not necessarily be worked out, but they serve as a "stand by" in case the stars are obscured. For a similar reason observations should be taken when land is about to be made, for if a fog comes on these observations may be worked out and will prove most valuable.

The estimated position with which to find the position line should be ascertained as accurately as possible, although the position line can be found equally well by using an estimated position which is many miles in error. The reasons for this are :—(1) the necessity of developing a habit of always making as careful an estimate as possible of the ship's position ; (2) as soon as the magnitude and direction of an intercept has been ascertained, the difference between the ship's probable position and the estimated position is immediately apparent.

When observing the meridian altitude of a body which is passing nearly overhead, it is advisable to note by compass the position on the horizon of either the North or South point, depending on whether the body is passing to the North or South of the observer, and, at the correct time, to observe the altitude above that point. It may happen that the supplement of the altitude has been observed, either inadvertently or because the horizon was partially obscured ; in such a case it should be corrected as shown in the following example.

Example :—On March 28th, 1914, the supplement of the altitude of the sun's L.L., measured to the North point of the horizon, was observed to be 94° 16′ 30″ ; I.E., + 1′ 30″ ; H.E., 50 feet.

Obs. alt. $\underline{\odot}$ to N. point of horizon -	94° 16′ 30″
I.E. - - - - -	+1 30
	94 18·0
Dip - - - - -	−6·9
App. alt. $\underline{\odot}$ to N. point of horizon -	94 11·1
	180 00
App. alt. $\overline{\odot}$ to S. point of horizon -	85 48·9
Refraction - - - -	− ·1
	85 48·8
S.D. (U.L.) - - - -	−16·0
True alt. sun's centre to S. point of horizon - - - -	85 32·8

CHAPTER XV.

RISING AND SETTING OF HEAVENLY BODIES, TWILIGHT, &c.

133. Hour angles of heavenly bodies when on the rational horizon.—At sea it may frequently be necessary to determine whether there will be sufficient light at a particular time to enable objects to be recognised, and for this reason we have to consider the times at which a heavenly body rises and sets.

The times of rising and setting of a heavenly body are the times at which its centre is on the rational horizon East and West of the meridian respectively.

In Fig. 122, let X' and X be the true places of a heavenly body when on the rational horizon East and West of the meridian respectively, then $24^h - ZPX'$ is the hour angle of the body when rising, and ZPX is the hour angle when setting. In order to find the times of rising or setting of a heavenly body it is first necessary to determine this angle (ZPX' or ZPX).

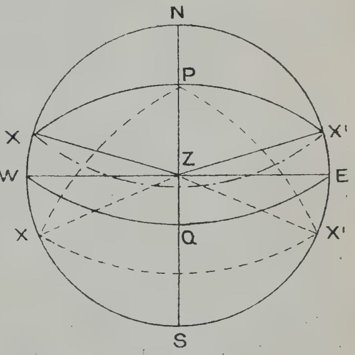


Fig. 122.

Let L be the latitude of the observer, and D the declination of the heavenly body, L and D being of the same name, that is, both North or both South. In the triangle PZX

$$\cos ZPX = \frac{\cos ZX - \cos PX \cos PZ}{\sin PX \sin PZ};$$

therefore, denoting the hour angle by H and remembering that when a body is on the rational horizon its zenith distance is 90°, we have $\cos H = -\cot PX \cot PZ$.

Now, $PX = 90° - D$, and $PZ = 90° - L$.

Therefore $\cos H = -\tan D \tan L$, or $\cos(12^h - H) = \tan D \tan L$.

If L and D are of different names PX is $90° + D$, and if we denote the hour angle in this case by H' we have $\cos H' = \tan D \tan L$.

From these formulæ we see that $H' = 12^h - H$.

The hour angles at setting (H) are tabulated in the Abridged Nautical Almanac for values of L from 0° to 70° and of D from 0° to 30°, when L and D are of the same name. The hour angles at rising are found by subtracting the tabulated results from 24 hours.

When *L* and *D* are of different names the hour angles at setting are found by subtracting the tabulated results from 12 hours. The hour angle at rising is found by subtracting this amount from 24 hours.

The table takes no account of dip, semi-diameter, refraction or parallax, so it must not be expected that a heavenly body becomes visible, or disappears, exactly when its hour angle is that given in the table.

134. S.M.T. of visible sunrise and visible sunset.—In the case of the sun the tabulated hour angle is the S.A.T. of sunset, and when subtracted from 24 hours the result is the S.A.T. of sunrise.

Now let us consider what is the observed altitude of the sun when it is on the rational horizon, that is, when its true altitude is zero.

Sun's true altitude	0° 00′
Refraction and parallax	+29
Apparent altitude	0 29

From this we see that at sunset or sunrise the sun's centre appears to be about 29′ above the horizon, and taking the semi-diameter as 16′, the sun's L.L. at sunset or sunrise is about 13′, or about a semi-diameter, above the horizon.

Therefore the times at which the sun is seen to rise and set, that is, the times of visible sunrise and visible sunset, differ by a small amount from the times at which the sun is on the rational horizon, so that, by applying a small correction to the time given in the Abridged Nautical Almanac, we can find the time of visible sunset or the time of visible sunrise.

The following investigation shows how this correction is obtained :—

Obs. alt. sun's U.L.	0° 00′ 00″
Dip for 20 ft.	−4 24
	−0 04 24
Refraction	−35 32
	−0 39 56
Parallax	+9
	−0 39 47
S.D.	−16 00
True alt. sun's centre	−0 55 47

and assuming 20 feet as the average height of the observer's eye, the correction required is the time the sun takes to change its altitude 55′·8 at the time of rising or setting.

In Figs. 123 and 124, let X be the true place of the sun when on the rational horizon West of the meridian. In Fig. 123 L and D are of the same name, and in Fig. 124 they are of different names. Let BX' be the change in altitude $= dz$ $(55{\cdot}8')$ and XPX' the corresponding change in hour angle $= dH$.

In the triangle XBX', the sides are so small that the triangle may be considered a plane triangle right-angled at B.

Now $dH = XX' \sec D$ (§ 12);
also $XX' = BX' \operatorname{cosec} BXX' = BX' \operatorname{cosec} PXZ = dz \operatorname{cosec} PXZ$.

Therefore $dH = dz \sec D \operatorname{cosec} PXZ$.

In the triangle PZX, $ZX = 90°$, and therefore by the rule of sines,

$$\operatorname{cosec} PXZ = \sec L \operatorname{cosec} H.$$

$$\text{Therefore } dH = dz \sec D \sec L \operatorname{cosec} H$$

$$= \frac{dz}{\sin H \cos D \cos L}$$

Now, as H is the hour angle at sunset, $\cos H = \pm \tan D \tan L$

$$\therefore \sin H = \sqrt{1 - \cos^2 H} = \sqrt{1 - \tan^2 D \tan^2 L}$$

$$= \frac{\sqrt{\cos^2 D \cos^2 L - \sin^2 D \sin^2 L}}{\cos D \cos L}.$$

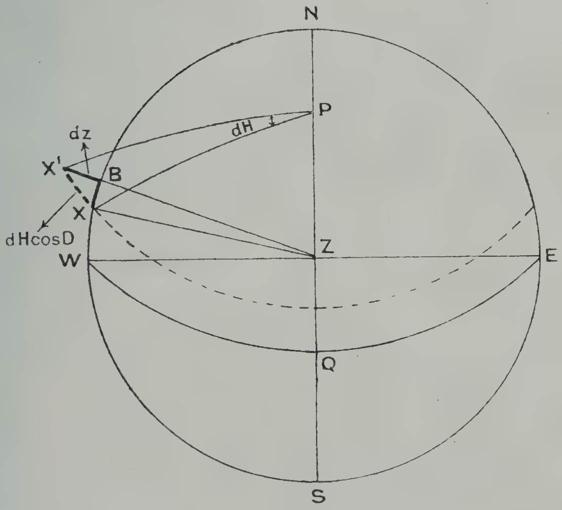


Fig. 123.

$$\therefore \sin H = \frac{\sqrt{\cos (D + L) \cos (D - L)}}{\cos D \cos L}$$

$$\therefore \sin H \cos D \cos L = \sqrt{\cos (D + L) \cos (D - L)}.$$

$$\therefore dH = \frac{dz}{\sqrt{\cos (D + L) \cos (D - L)}}.$$

Therefore, if dH is in minutes of time and dA in minutes of arc, we have $dH = \frac{dz}{15}\sqrt{\sec(D+L)\sec(D-L)}$.

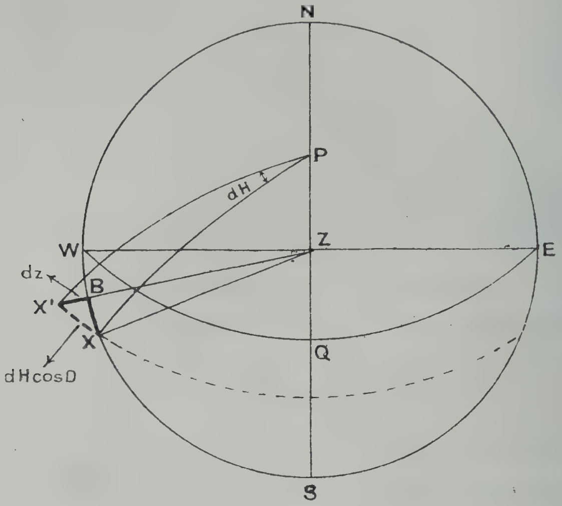


Fig. 124.

The following table has been calculated from this formula, dz being taken as $55'\cdot8$ which corresponds to a height of eye of 20 feet; the numbers given in the table are the minutes that should be added to the S.A.T. of sunset, or subtracted from the S.A.T. of sunrise, to obtain the S.A.T. of visible sunset or visible sunrise. The purpose for which this problem is most often required is to find the time at which to fire the sunset gun when in harbour; the error, due to the height of eye being more or less than 20 feet, is very small and need not be considered.

	Latitude.							
	0°	10°	20°	30°	40°	50°	60°	65°
Declination.								
0°	3·7	3·8	4·0	4·3	4·9	5·8	7·4	8·8
10°	3·8	3·8	4·0	4·4	5·0	6·0	7·9	9·7
20°	4·0	4·0	4·2	4·7	5·4	6·8	10·2	15·0
23°	4·0	4·1	4·4	4·8	5·6	7·3	11·9	23·1

Example:—On April 29th, 1914, at Bermuda, Latitude 32° 22′ N., Longitude 64° 30′ W., it is required to find the time at which to fire the sunset gun.

Rough S.A.T. sunset - 6^h 00^m April 29th.
Long. - - - 4 18 (W.)

G.D. - - - - 10 18 April 29th.

Declination for G.D. 14° 25′ N.
Equation of time for G.D. 2^{m} 41^{s} – to A.T.

From the Abridged Nautical Almanac, the hour angle at setting is found to be 6^{h} 38^{m}.

S.A.T. sun's centre on rational horizon		6^{h} 38^{m}
Correction from preceding table	-	+4·6
S.A.T. sun's U.L. on sea horizon	-	6 42·6
Eq. T. - - -	-	–2·7
S.M.T. sun's U.L. on sea horizon	-	6 39·9

The time of visible sunset is therefore 6^{h} 40^{m} P.M., and this is the time required.

135. Twilight.—Owing to the reflection of light from the atmosphere a certain amount of light is received from the sun when below the horizon, and this is called twilight.

There are two periods of twilight, evening twilight and morning twilight.

Astronomical twilight is assumed to begin in the morning, and to end in the evening, when the sun's centre is 18° below the horizon. During this time stars of the 2nd magnitude are not visible to the naked eye.

Civil twilight is assumed to begin in the morning, and end in the evening, when the sun's centre is 6° below the horizon, and during this time stars of the 1st magnitude are not visible to the naked eye. The duration of civil twilight is about one-third of the duration of astronomical twilight, but is less than one-third when the latter is very long.

Astronomical twilight lasts all night when the latitude and declination are of the same name and their sum is not less than 72°.

Twilight is necessarily short within the tropics, because the apparent path of the sun is there more nearly perpendicular to the horizon than in higher latitudes.

The times of cessation and commencement of twilight may be calculated from the astronomical triangle *PZX*, the zenith distance being taken as 108° for astronomical twilight, and as 96° for civil twilight.

Example:—On April 27th, 1914, in Lat. 50° 00′ N., Long. 45° 00′ W., it is required to find the duration of astronomical evening twilight.

As a general rule the time will not be required to any great degree of accuracy; it is therefore sufficient to take out the declination of the sun for the G.D. of sunset.

Rough S.A.T. sunset -	-	6^{h} 00^{m}	April 27th.
Longitude - -	-	3 00	(W.)
G.D. - - -	-	9 00	April 27th.

Declination for G.D., 13° 46′ N.

From Abridged Nautical Almanac, the hour angle at setting is $7^h\ 07^m$.

S.A.T. sun's centre on rational horizon	$7^h\ 07^m$
Correction from table (§ 134) - -	+6·3
S.A.T. sun's U.L. on sea horizon -	7 13·3

In Fig. 125, let *X* be the true place of the sun when 18° below the rational horizon, so that *ZX* = 108°. Then in the astronomical triangle *PZX*, the S.A.T. (*H*) is calculated from the formula :—

$$\text{hav } H = \sec L \sec D \sqrt{\text{hav }[z + (L \mp D)] \text{ hav }[z - (L \mp D)]}.$$

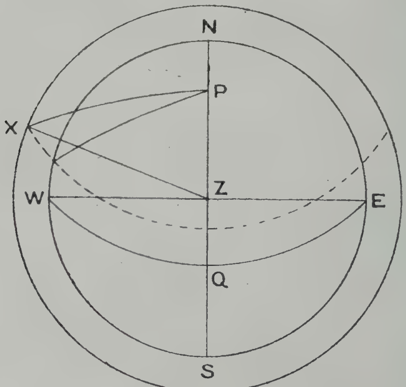


Fig. 125.

Lat.	50° 00′ N.	*L* sec	10·19193
Dec.	13 46 N.	*L* sec	10·01266
(*L* -- *D*)	36 14		
z	108 00		
z + (*L* − *D*)	144 14	½ *L* hav	4·97849
z − (*L* − *D*)	71 46	½ *L* hav	4·76799
H	$9^h\ 27^m\cdot6$	*L* hav *H*	9·95107

S.A.T. at end of twilight	$9^h\ 27^m\cdot6$
S.A.T. visible sunset	7 13 ·3
Duration of astronomical evening twilight	2 14 ·3

136. S.M.T. of visible moonrise and visible moonset.—Let us first consider what is the altitude of the moon's centre when the observed altitude of the moon's U.L. is zero.

Observed altitude moon's U.L.	0°	00′	00″
Dip for 20 feet	−	4	24
	−0	04	24
Refraction	−	35	32
	−0	39	56
Average parallax		+57	30
	0	17	34
Semi-diameter		−15	45
True altitude moon's centre	0	01	49

From this we see that the appearance of the moon's U.L. on the sea horizon at rising, and its disappearance at setting, takes place very nearly (within less than one minute in Lat. 60°) at the same time as the arrival of the moon's centre on the rational horizon.

The times of moonrise and moonset are constantly required, but seldom to a great degree of accuracy, the time to the nearest two or three minutes being generally sufficient.

The table in the Abridged Nautical Almanac, for finding the times of rising and setting of a heavenly body, does not give the interval in solar hours between the times of rising or setting and the time of meridian passage of any heavenly body, other than the sun. As the moon takes roughly 24^h 50^m from one meridian passage to another, or while changing its hour angle 360° or 24 hours, the interval of mean solar time in passing through any hour angle is greater than that hour angle, by an amount depending on the mean solar interval between two successive meridian passages of the moon, as shown in the following example:—

Example:—On March 12th, 1914, in Lat. 60° N., Long. 150° W., it is required to find the S.M.T. of moonrise and moonset.

M.T. of upper meridian passage at Greenwich	12^h	52^m	Mar. 12th.
Correction for 150° W. and diff. 52^m	0	22	
S.M.T. meridian passage	13	14	Mar. 12th.
Longitude in time	10	00 (W.)	
G.D. of meridian passage	23	14	Mar. 12th.

Moon's declination for above G.D., 6° S.

From Abridged Nautical Almanac, hour angle, 5^h 18^m.

G.M.T. of meridian passage -	23^h 14^m	
Hour angle - - -	5 18	
G.D. of rising - -	17 56	Mar. 12th.
G.D. of setting - -	4 32	Mar. 13th.

Rising.		*Setting.*	
G.D. 17^h 56^m Mar. 12th.		G.D. 4^h 32^m Mar. 13th.	
Declination 4° 36′ S.		Declination 7° 40′ S.	
Hour angle from table -	5^h 28^m	Hour angle from table -	5^h 06^m
Correction for 5^h 28^m and diff. 52^m - -	0 12	Correction for 5^h 06^m and diff. 52^m - -	0 11
Interval between rising and meridian passage	5 40	Interval between mer. passage and setting -	5 17
S.M.T. meridian passage	13 14	S.M.T. meridian passage	13 14
S.M.T. moonrise - -	7 34	S.M.T. moonset -	18 31

137. Identification of stars.—It frequently happens that the sky is partially obscured by clouds and that only a few of the heavenly bodies are visible, and sometimes only one star in any particular constellation can be seen. Under such conditions it is impossible to ascertain the name of any particular body, that may be visible, by means of imaginary lines in the heavens such as were described in § 75. A book entitled "What Star is it?" (Harvey), a copy of which is supplied to each of H.M. Ships, affords a means of identifying any heavenly body from its altitude and compass bearing.

The book consists of the solutions of a large number of spherical triangles. On the left hand page are tabulated the hour angles and on the right hand page the declinations corresponding to the three known data—latitude, altitude, and azimuth. These hour angles and declinations are tabulated for every 5° of latitude from 0° to 65°, and for every 5° of altitude from 10° to 65°, and for every 10° of azimuth. Thus, if a body's altitude is observed, and at the same time its bearing is noted by compass and so its true bearing obtained, the hour angle and the declination of the body can be obtained.

In Fig. 126, which is on the plane of the celestial equator, PZ is the meridian of the observer, X and Y are the true places of two stars West and East of the meridian respectively, ♈ is the first point of Aries. XPZ is the hour angle of X as obtained from the tables, YPZ is 24^h —hour angle of Y as obtained from the tables, and we have

R.A. of $X = \Upsilon PZ - XPZ =$ R.A.M. $-$ hour angle of X.

R.A. of $Y = \Upsilon PZ + ZPY =$ R.A.M. $+$ hour angle of Y from tables.

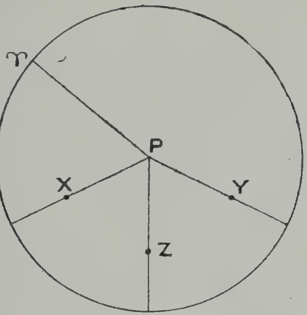


FIG. 126.

Thus we have the following rule :—

Star E.,—add hour angle to R.A.M. for star's R.A.

Star W.,—subtract hour angle from R.A.M. for star's R.A.

Example :—On March 26th, 1914, in Lat. 50° N., Long. 45° W., at 5^h 55^m P.M. (S.M.T. nearly), the altitude of a star was observed to be 50° 10′, and the compass bearing to be S. 76° W. Required the name of the star.

S.M.T.	-	5^h 55^m	Mar. 26th.	R.A.M.S.	-	0^h 14^m
Long.	-	3 00	(W.)	S.M.T.	-	5 55
G.D.	-	8 55	Mar. 26th.	R.A.M.	-	6 09

Compass bearing	- -	S. 76° W.
Deviation	- - -	1 W.
Magnetic bearing	- -	S. 75 W.
Variation from variation chart	-	33 W.
True bearing	- - -	S. 42 W.

Entering the tables with Lat. 50° and altitude 50° 10′ we find, opposite star's true bearing 42° (latitude and bearing contrary names), that the hour angle is 1^h 46^m and the declination is 16° N.

R.A.M.	- - -	6^h 09^m
H (Star W. subtract)	- -	1 46
R.A.✳	- - - -	4 23

From the list of stars at the end of the book we find that Aldebaran has right ascension $4^h\ 30^m$ and declination 16° 3′ N. and that this is the only star that will satisfy the data.

Should there be no star whose right ascension and declination agree with the calculated right ascension and declination it is probable that a planet has been observed, and in such a case search should be made among the planets in the Nautical Almanac.

Should there be two or three stars whose right ascensions and declinations are so near to one another as to make it difficult to determine which has been observed, it will be necessary to interpolate between the numbers given in the table, in order to find the star's right ascension and declination more exactly, but this is seldom necessary.

As one of the arguments, with which the tables are entered, is the true bearing of the body, it should be made a rule, whenever a star is observed, to note the compass bearing at the time of observation.

The name of an unknown star may be more easily found when a Star Globe or Star Finder is available. This instrument is particularly useful, not only for the purpose for which it is designed, but for general instruction in astronomy.

138. Torrid, Frigid, and Temperate zones.—The declination of the sun varies from 23° 27′ N. to 23° 27′ S.; therefore since the latitude of the geographical position of a heavenly body is equal to the declination of the body (§ 109), the sun is always in the zenith of some place on the earth's surface situated between the parallels of latitude 23° 27′ N. and 23° 27′ S.

That part of the surface of the earth which is bounded by the equator and the parallel of latitude of 23° 27′ N. is called the North Torrid zone; similarly, that bounded by the equator and the parallel of latitude 23° 27′ S. is called the South Torrid zone. These two zones are frequently spoken of as The Tropics.

That circle of position, whose centre is the geographical position of the sun at any instant, and which corresponds to a true zenith distance of 90°, is called the circle of illumination at that instant, because the sun is visible at every point within it. It divides the surface of the earth into two hemispheres, the illuminated and the dark.

At any point on the circumference of the circle of illumination the sun is on the rational horizon of that point.

When the geographical position of the sun is on the equator, that is, when the declination is 0°, the circle of illumination passes through both poles as in Fig. 127. When the geographical position of the sun is in Lat. 23° 27′ N., that is, when the sun has its maximum North declination, the illuminated hemisphere (bounded by the circle of illumination *AB*, Fig. 128), contains the North pole. As the earth revolves in the direction shown by the arrow, the points *A* and *B*, which are the points on the circle of illumination of maximum latitude North and South, trace out the parallels of latitude of 66° 33′ N. and 66° 33′ S. Therefore, when the declination of the sun is 23° 27′ N., the sun will not set at any point North of the parallel of 66° 33′ N. and will not rise at any point South of the parallel of 66° 33′ S. When the declination of the sun is 23° 27′ S. the converse takes place.

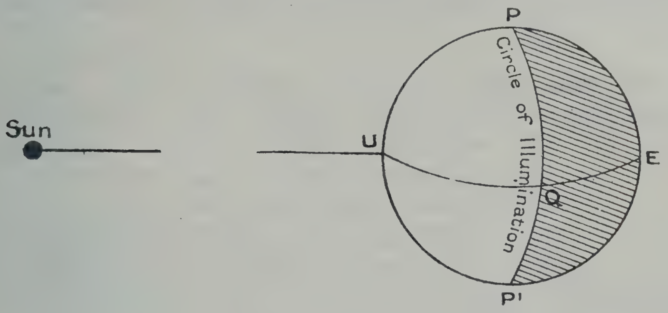


Fig. 127.

That part of the surface of the earth which extends from the North pole to the parallel of 66° 33′ N. is called the Arctic zone, and the corresponding part in the Southern hemisphere is called the Antarctic zone. These two zones, when referred to together, are termed the Frigid zones.

The area which is included between the parallels of 23° 27′ N. and 66° 33′ N. is called the North Temperate zone, and the corresponding part in the Southern hemisphere is called the South Temperate zone.

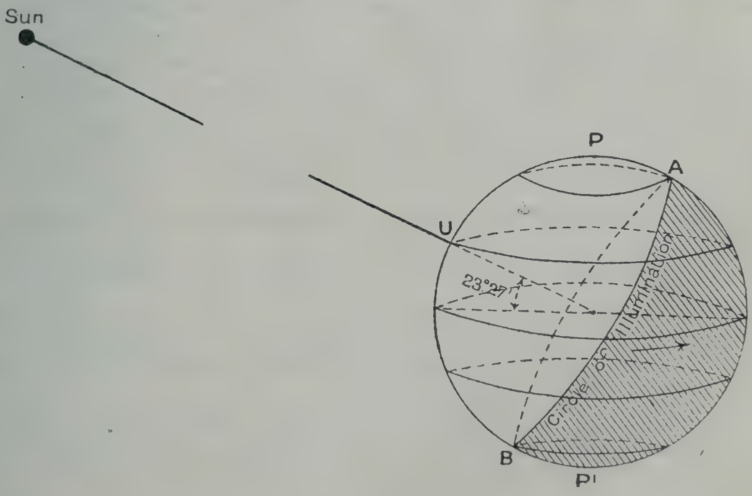


Fig. 128.

CHAPTER XVI.

THE ERROR AND RATE OF THE CHRONOMETER.

139. Meaning of the terms error, rate, and accumulated rate.—The principle and description of the chronometer will be found in Part IV.; we are here concerned with the problem of finding the error and rate of the chronometer. By the error of a chronometer we mean the difference between the time shown by it at any instant and the G.M.T. at the same instant. It is convenient always to consider that a chronometer is slow, in order that the G.M.T. may be found by adding the error to the time shown by the chronometer.

The error of a chronometer varies from day to day, and in a good instrument the daily change in the error remains approximately constant. This daily change is called the rate of the chronometer, and is said to be a gaining or losing rate according as the chronometer is gaining or losing. All H.M. Ships are supplied with three chronometers and one deck watch. When supplied to a ship, the chronometers are accompanied by tabular statements showing their rates during the past few weeks, and from these, estimates may be made as to their reliability. It is customary to label the chronometers *A*, *B*, *C*, &c., according to the estimate made, *A* being considered the most reliable and adopted as the standard.

In order to obtain the G.M.T. at any instant, it is necessary to know the error of the chronometers at that instant, and this error depends on the error determined at some previous date, and on the accumulated rate, which is the increase or decrease of the error of the chronometer in the interval. Thus the accuracy of the G.M.T., found from a chronometer at any instant, depends on the accuracy of the accumulated rate. Now accumulated rate in an interval = daily rate × number of days, so that the accuracy of the G.M.T. depends on the accuracy with which the chronometer has maintained its daily rate.

140. System of daily comparisons.—In order to determine whether the chronometers are working steadily, recourse is had to a system of daily comparisons the results of which are entered in a book called the chronometer journal. This system consists of comparisons between the *A* chronometer and all the other chronometers and deck watches in the ship, and is carried out as follows:—

[Chronometers beat every half second, chronometer watches and deck watches usually beat five times in two seconds.]

When about to compare, only open the lid of *A* chronometer, so that its tick may sound loudly and that of the others may be deadened. Write down a time which *A* is going to show, say

$4^h\ 16^m\ 30^s\cdot0$., and start counting the beats when the second hand gets to 20 seconds, thus:—Half, one, half, two, half, three, &c.; in a few moments the beats can easily be counted; then still counting the beats turn the eye to the other chronometer, and note exactly what its second hand shows at the instant you hear *A* beat the exact second decided on. Write down the comparison as follows:—

$$\begin{array}{llll} A - & 4^h & 16^m & 30^s\cdot0 \\ B - & 4 & 27 & 28\cdot5 \\ \hline B - & 11 & 49 & 01\cdot5 \text{ slow on } A. \end{array}$$

Compare again as a check on the first comparison.

The comparisons are usually all shown as slow on *A*; this saves, confusion, and enables the time by any other chronometer, or deck watch to be converted into time by *A* by using addition instead of subtraction. Similarly, all chronometer errors should be shown as slow on G.M.T. and not some fast and some slow.

With practice, chronometers can be easily compared to a quarter of a second, and accurate comparison is most important when finding the errors by observation.

The daily difference between the comparisons of any two chronometers is the difference between their daily rates; any alteration of the daily difference shows that one or both of the chronometers is going irregularly. If the daily difference of comparison between *A* and *B* remains constant at the approximate algebraic sum of their previously obtained daily rates, and that between *A* and *C* alters, it is probable that the rate of *C* chronometer has altered; thus, when finding the error of the deck watch from the chronometer journal in order to determine a position line, it is necessary to examine as to whether all the chronometers agree, and this is done as follows.

Apply to the estimated error of *B*, found as explained above, the comparison between *A* and *B*, and thus find the error of *A* on G.M.T., as indicated by the *B* chronometer. Similarly the error of *A* on G.M.T. as indicated by other chronometers may be found. Thus we find three or more possible errors for the *A* chronometer, an inspection of which will show the most probable error of *A*, and from this the error of the D.W. is determined. In the event of no one error appearing more probable than another, their mean should be assumed to be the error of *A*.

If a landfall has to be made, or a danger to be cleared, from a position obtained by astronomical observations, when there is a considerable disagreement between the several chronometers as to the error of *A*, that error should be selected which places the ship in the most disadvantageous position (§ 118).

141. How to take time accurately with a deck watch.—Accurate time-taking is of special importance when taking observations for obtaining the errors of chronometers.

A practised time-taker can take time with a good deck watch to one-fifth of a second. A deck-watch beats five times in two seconds; the beats are therefore 0·4 second apart, and consequently the beat of a watch coincides exactly with every even second. Beginning at, say, 8 seconds

the 1st beat afterwards would be 8^{s}·4
„ 2nd „ „ „ 8·8
„ 3rd „ „ „ 9·2
„ 4th „ „ „ 9·6
„ 5th „ „ „ 10·0

The time-taker looks at the watch and starts counting from an even second, every time the watch beats, until the next even second is reached, 4, 8, 2, 6, 0, 4, 8, 2, 6, 0, 4, 8, 2, 6, 0 and so on, until he hears the observer call "'top." If the "'top" coincides exactly with one of the beats, the time-taker can exactly recognise from his counting which decimal of a second corresponds to the "'top," and his eye tells him which second. With practice it is possible to interpolate between the beats.

When taking time for any kind of observation, the time-taker should insist on the observer looking at the watch, after the last observation of the set has been taken, to satisfy himself that the correct minute has been put down.

142. Error of the chronometer by time signal.—The error of a chronometer may be found, either by comparison with a clock whose error is exactly known, or by astronomical observation. The standard clock at every observatory is regulated daily by means of observations taken with a transit instrument, and this clock can be placed in electrical communication with the telegraphic system; by this means, at a certain hour every day, a signal is transmitted to telegraph offices and port authorities for the purpose of regulating their clocks. In the United Kingdom the signal is transmitted from Greenwich at 10 A.M. This signal automatically adjusts certain clocks so that they show G.M.T., and from each of them a time signal is worked. At most important ports a signal is made for the convenience of shipping, and this usually consists of the automatic release of a ball from the yard-arm of a signal station; the release is actuated electrically by the standard clock at the place, or direct from the observatory. The whereabouts and times of time signals are given on the charts and in the sailing directions; full details of each signal are given in the Admiralty List of Lights and Time Signals. When observing a time signal the following procedure should be adopted. Holding the deck watch in one hand, take up such a position that the time signal is clearly visible, and about ten seconds before the signal is expected begin counting as explained (§ 141). Write down the time shown by the deck watch at the instant the ball begins to fall. Immediately proceed to the chronometer room and compare the D.W. with the *A* chronometer, and the other chronometers with the *A* chronometer. From these comparisons the errors of all the chronometers may be found.

Time signals are also transmitted from various high power wireless telegraphy stations, and comparison with such signals is a very convenient method of finding the error of the chronometers, when at a place where no time signal exists; when using this method consideration should be paid to the table of safe distances given in Part IV.

When some considerable time must elapse between the finding of the error of the D.W. and the subsequent comparison, such as when the D.W. has to be conveyed ashore for comparison with a standard clock, consideration should be given to the following article.

143. The mean comparison.—It is of no use obtaining the G.M.T., however accurately it may be done, unless it can be conveyed accurately to the chronometers. Suppose *A* has a steady gaining rate of 7 seconds per day and the D.W. a losing rate of 10 seconds per day, it is obvious that the comparison between them cannot remain constant for even an hour. When the rates are steady, it follows that if comparisons are made before landing, when necessary to do so to obtain the error, and again after returning, a comparison may be deduced which would be correct for any particular instant between the two comparisons actually taken; this calculated comparison is called a mean comparison, and is found as follows:—

Comparison before landing:—

Time by *A* - - - -	8^h	39^m	00^s
„ „ D.W. - - - -	8	24	07·2
D.W. slow on *A* - - -		14	52·8

Comparison after return:—

Time by *A* - - - -	10^h	40^m	00^s
„ „ D.W. - - - -	10	25	10·0
D.W. slow on *A* - - - -	0	14	50·0

Elapsed time between comparisons by D.W. = $2^h\ 01^m\ 03^s = 121^m$.

D.W. time at which error was observed	9^h	57^m	20^s
D.W. time of last comparison - -	10	25	10
Elapsed time - - - -	0	27	50 = $27^m\cdot8$

By first comparison D.W. is $14^m\ 52^s\cdot8$ slow on *A*,
„ second „ „ „ 14 50 „ „ *A*;

therefore in 121^m the D.W. has gained $2^s\cdot8$ on *A* and in $27^m\cdot8$ the D.W. will gain $\dfrac{27\cdot8 \times 2\cdot8}{121} = \cdot64^s$.

By the second comparison the D.W. was $14^m\ 50^s$ slow on *A*; therefore, at the time at which the error was observed it was $0^h\ 14^m\ 50^s\cdot69$ slow on *A*, which is the mean comparison.

144. Error of the chronometer by astronomical observations.—To find the error of the chronometer if there is no time signal available—that is, to find the difference between the time shown by the chronometer at any instant and the G.M.T.—necessitates our finding the G.M.T. by observation.

In the case of the sun,

$$\text{G.M.T.} = \text{M.T.P.} \pm \text{Long.} = \text{A.T.P.} \pm \text{Eq. T.} \pm \text{Long.}$$

In the case of other heavenly bodies

$$\text{G.M.T.} = H. + \text{R.A.}\,\ast - \text{R.A.M.S.} \pm \text{Long.}$$

From these equations we see that the only unknown term on the right hand side is the hour angle of the body. Now if we know the latitude, longitude, and altitude exactly, the hour angle of the body can be calculated as explained in § 130.

The altitude of a heavenly body should be observed as accurately as possible when it is desired to obtain the error of the chronometer. Any error in the altitude not only affects the error of the chronometer deduced from the altitude, but affects every position of the ship that subsequently depends on that error. For a similar reason the observation is usually taken on shore at a place the latitude and longitude of which are exactly known. The altitude is not taken above the sea horizon because of the unreliability of all altitudes measured from it, but the observer has recourse to an instrument called the artificial horizon, one or more of which are supplied to each of H.M. Ships. In the event of it being impossible to go on shore the altitudes may be observed above the sea horizon, but in such a case the results must be considered as approximate only.

145. The artificial horizon.—This usually consists of a shallow rectangular trough, *BC*, Fig. 129, filled with pure

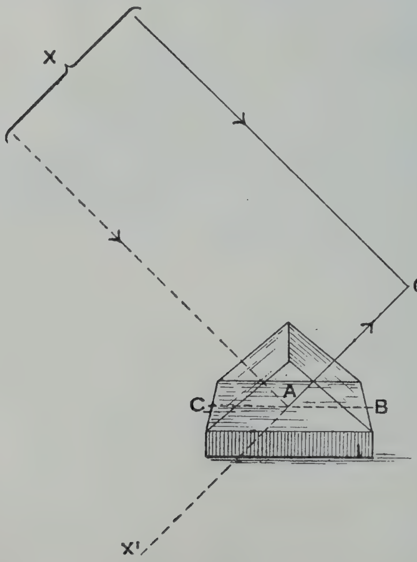


Fig. 129.

mercury, the surface of which forms a perfectly horizontal plane. except near the edges. A ray of light from a body X is reflected from BC in the direction AO, which makes an angle OAB with the plane of the mercury = angle XAC in accordance with the law in optics "the angle of incidence is equal to the angle of reflection."

An observer whose eye is at O, sees, on looking into the mercury, an image of X proceeding apparently from the point X' along the straight line AO, and he measures the angle XOX', which is the observed altitude in the artificial horizon.

Since the angle $OAB = X'AC$, the angle $X'AC = XAC$, so that the angle $XOX' = XAX' = 2\ XAC$ = twice the apparent altitude of X.

From this we see that, provided that the surface of the mercury is horizontal, an observed altitude of a heavenly body in an artificial horizon, after instrumental errors of the sextant have been applied, is twice the apparent altitude of the body, and that the dip is not involved.

To obviate the disturbing effects of wind on the surface of the mercury, a glass roof, Fig. 129, is placed over the artificial horizon. The two sheets of glass in the roof fit loosely in the frame so as to avoid the possibility of the glass being warped due to the unequal coefficients of expansion of the metal frame and the glass. The surfaces of the glass plates are ground as nearly parallel as is possible, but, owing to the possibility of their not being quite parallel, it is advisable to mark one side of the roof with a white paint mark and to take half the observations with this mark on the right, and half with the mark on the left; the practice varies with different kinds of observations, and this point will be dealt with further on.

The artificial horizon does not admit of observations being taken when the altitude is less than 15°. When taking observations with this instrument, the eye should be in such a position that the image of the body appears in the centre of the mercury. Practical rules which should be followed when taking observations on shore for obtaining the error of the chronometer, together with remarks on the selection of the position for setting up the artificial horizon, will be found at the end of this chapter.

146. Observations in the artificial horizon.—We will now consider how the observation is taken.

The observer O, Fig. 130, sees the sun at X and sees the reflected image of the sun at X'. If U and L represent the upper limb and lower limb respectively of the sun, then U' and L' represent the reflected images of the upper limb and lower limb respectively.

Suppose that an observer takes the altitude of the sun's lower limb in an artificial horizon (obs. alt. $\underline{\odot}$). The angle measured is LOL' (Fig. 130). Now,

$$LOL' = LAL' = 2\ LAC = 2 \text{ App. Alt. } \underline{\odot}.$$

Similarly, when the altitude of the upper limb (Obs. Alt. $\overline{\odot}$) is taken, we have

$$UOU' = UAU' = 2\ UAC = 2 \text{ App. Alt. } \overline{\odot}.$$

Therefore, in either case, the measured angle is twice the apparent altitude of the limb observed. The observed double altitude is written D. Alt.

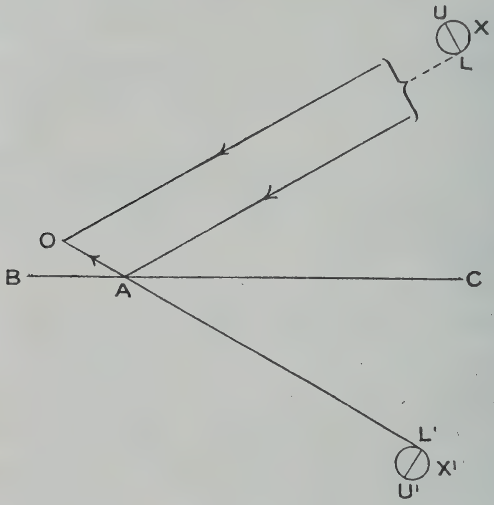


Fig. 130.

Suppose that observations are being taken in the morning, that is, when the altitude is increasing, then from Fig. 130 we see that, if the lower limb is being observed, the two reflected images, one L from the mirror of the sextant and the other L' from the artificial horizon, are separating; similarly, if the upper limb is being observed the two images are closing. The opposites take place when observations are being taken in the afternoon. This may be briefly expressed as follows:—

A.M.	Closing suns - - - -	U.L.
	Opening suns - - - -	L.L.
P.M.	Closing suns - - - -	L.L.
	Opening suns - - - -	U.L.

Attention to this rule will prevent a mistake being made as regards which limb of the sun has been observed.

Observations should be taken at equal intervals of altitude as follows. Set the index of the sextant to an exact 10′ of arc and call " 'top " when the contact takes place; then set the index 10′ forwards or backwards, according as the body is rising or setting; watch for the contact and call " 'top " again, and so on until the set is complete. If the body is moving so fast that it is impossible to set the sextant at every 10′ of arc, the observations should be taken at every 20′ of arc. By following this mode of procedure, all the observations will have been taken at equal intervals of altitude and the time interval between successive observations should be nearly the same. An inspection of the time intervals between successive observations will make it plain whether the set is reliable or not. An odd number of observations should be taken to simplify taking the mean of the results.

In observations at sea very great accuracy in calculation is not only unnecessary, but is a waste of valuable time when it is desired to obtain the position of the ship as rapidly as possible. In shore observations for time there is no such necessity for haste, and, as mentioned above, the accuracy of all positions subsequently obtained depends on the time. Therefore, in working out shore observations, every care should be taken that the elements and corrections are as accurate as possible, and interpolation should be made use of when taking out the logarithms. For this reason, when working out these observations, the elements should be taken from the unabridged Nautical Almanac, one copy of which is supplied to each of H.M. Ships.

In this Almanac the declination of the sun is tabulated to decimals of a second of arc; the equation of time and the right ascension of the mean sun are tabulated to the second decimal place of a second of time. The declination and equation of time should be taken from page II. of the month, where they are tabulated for Greenwich mean noon; the right ascension of the mean sun should be taken from the column headed "Sidereal Time," and should be corrected by means of the table at the end of the Almanac for converting intervals of mean solar time into equivalent intervals of sidereal time; this table is simply an extension of that given on page I. of the month in the Abridged Nautical Almanac for the correction of the R.A.M.S. The elements for the planets should be taken from that part of the unabridged Almanac where they are tabulated under the heading "Mean Time,"; the elements for the stars should be taken from that part where they are tabulated for every tenth day.

The double altitude observed should be corrected for index error; it should also be corrected for another instrumental error of the sextant called centering error (C.E.). The result divided by 2, as explained above, gives the apparent altitude of the limb which has been observed. The mean refraction for this altitude should then be applied and its correction for barometer and thermometer; the semi-diameter should then be applied, and, lastly, the parallax in altitude.

It is most important that the latitude and longitude of the spot where the observations are taken should be correctly known. If the "observation spot" is used, which is a point marked on the chart whose latitude and longitude were accurately determined during the survey of the locality, the latitude and longitude of this spot will be found in the title of the chart. If any other place is selected, its position must be fixed on the chart; this can generally be done by sextant angles, the *d* Lat. and *d* Long. between the place and the observation spot being measured off and applied to the known latitude and longitude of the latter.

Observations for error of chronometer are of two kinds:—

(*a*) Absolute altitudes, by which is meant observations on one or both sides of the meridian worked in a manner similar to the "longitude by chronometer" method. (§ 130.)

(*b*) Equal altitudes, by which is meant noting the times when the body had equal altitudes E. and W. of the meridian.

147. Error of the chronometer by absolute altitudes.—Under absolute altitudes are included three kinds of observations:—

(*a*) Absolute altitudes of the sun or a star on one side of the meridian.

(*b*) Mean of the results of absolute altitudes of the sun taken A.M. and P.M.

(*c*) Mean of the results of absolute altitudes of stars taken East and West of the meridian.

The following examples show (1) the method of working a single set of absolute altitudes of the sun and (2) the method of working absolute altitudes of stars East and West of the meridian.

Example (1):—On March 3rd, 1914, at about $8^h\ 5^m$ A.M. (M.T.P. nearly), on the Observation Spot at Aden, Lat 12° 47′ 11″ N., Long. 44° 58′ 31″ E., the deck watch was slow on G.M.T. (approx.) $25^m\ 06^s$. I.E., – 1′ 50″. Barometer, 29·7 inches. Thermometer, 87° F.

The following observations were taken to determine the error of the chronometers on G.M.T. (Opening suns):—

	D.W.	Diff.	Obs. alt. $\underline{\odot}$	
	$4^h\ 37^m\ 17^s{\cdot}2$	20·0	49° 10′	Mark right.
	4 37 37 ·2	21·2	49 20	
	4 37 58 ·4	20·8	49 30	
	4 38 19 ·2	22·2	49 40	
	4 38 41 ·4	23·0	49 50	
	4 39 04 ·4	20·4	50 00	Mark left.
	4 39 24 ·8	20·8	50 10	
	4 39 45 ·6	20·4	50 20	
	4 40 06 ·0	22·0	50 30	
	4 40 28 ·0	20·0	50 40	
	4 40 48 ·0		50 50	
	11/429 30 ·2			
Mean	4 39 02 ·75		50 00	

				Dec.	
M.T.P.	$20^{h}05^{m}\ 0^{s}$ Mar. 2nd.	Obs. alt. $\underline{\odot}$	50° 00′ 00″	7° 01′ 59″·8 S.	57·36
Long.	2 59 54 ·1 (E.)	I.E.	−1 50	+ 6 37·5	6·93
G.D.	17 05 0 Mar. 2nd.		49 58 10	7 08 37·3 S.	17208
		C.E.	+40		51624
D.W.	$4^{h}\,39^{m}\,03^{s}$				34416
Slow	25 06	App. alt. $\underline{\underline{\odot}}$	2/49 58 50		60/397·5048
	5 04 09	App. alt. $\underline{\odot}$	24 59 25		6′ 37″·5
	12 00 00	Mean ref.	−2 05	Eq. T.	
G.M.T. approx.	17 04 09		24 57 20	$12^{m}\,14^{s}$·52+to A.T.	
		Cor. to Mean ref.	−13	+ 3 ·60	52
					6·93
			24 57 07	12 18 ·12+to A.T.	
		S.D.	+16 09		1396
					3465
			25 13 16		3·6046
		Parallax	+8		
		True alt. $\odot$	25 13 24		
		True *z*	64 46 36		

L.	12° 47′ 11″N.	*L* sec	0·01091
D.	7 08 37 S.	*L* sec	0·00338
(*L.*+*D.*)	19 55 48		
z	64 46 36		
z+(*L.*+*D.*)	84 42 24	½ *L* hav	4·828467
z−(*L.*+*D.*)	44 50 48	½ *L* hav	4·581434
		L hav *H.*	9·424191

A.T.P.	$19^{h}\,51^{m}50^{s}$ 20
Eq. T.	+ 12 18 ·12
M.T.P.	20 04 08·32
Long.	2 59 54·1 (E.)
G.M.T.	17 04 14·22
D.W.	16 39 02·75
Slow	0 25 11·47

The deck watch was $25^{m}\ 11^{s}$·55 slow on G.M.T.
The following comparisons were made :—

Before landing—

A - - -	$7^{h}\ 11^{m}\ 00^{s}$
D.W. - - - -	3 47 15·2
D.W. slow - -	3 23 44·8 on *A*

After return on board—

A	$9^{h}\ 20^{m}\ 00^{s}$	*A*	$9^{h}\ 21^{m}\ 00^{s}$	*A*	$9^{h}\ 21^{m}\ 30^{s}$
D.W.	5 56 13·2	*B*	7 14 45	*C*	11 13 10·5
Slow	3 23 46·8	Slow	2 06 15	Slow	10 08 19·5 on *A*

Change in comparisons between D.W. and *A* in 2 seconds.

D.W. at 1st comparison	3^h	47^m	$15^s\cdot2$	
,, 2nd ,,	5	56	13·2	
Elapsed time by D.W.	2	08	58	$= 129^m$
D.W. at middle observation	4	39	02·75	
D.W. at 2nd comparison	5	56	13·2	
Elapsed time by D.W.	1	17	10·45	$= 67^m\cdot2$

$$\frac{67\cdot2 \times 2}{129} = 1^s\cdot04$$

D.W. slow on *A* on return	3^h	23^m	$46^s\cdot8$
			−1 ·04
Mean comparison, D.W. slow on *A*	3	23	45 ·76
D.W. slow on G.M.T.	0	25	11 ·47
A fast on G.M.T	2	58	34 ·29
	12	00	00
A slow on G.M.T.	9	01	25 ·71
B slow on *A*	2	06	15
B slow on G.M.T.	11	07	40 ·71
A slow on G.M.T.	9	01	25 ·71
C slow on *A*	10	08	19 ·5
C slow on G.M.T.	7	09	45 ·21

Example (2):—On April 29th, 1914, at about $6^h\ 45^m$ P.M. (M.T.P. nearly) at Hobart, Lat. 42° 53′ 22″ S., Long. 147° 20′ 28″ E., the deck watch was slow on G.M.T. (approximately) $11^h\ 53^m\ 00^s$. I.E., + 1′ 10″. Barometer, 28·3 inches. Thermometer, 43° F.

The following observations were taken to determine the errors of the chronometers on G.M.T. :—

Spica (E.).			*Rigel* (W.).		
D.W.	Diff.	Obs. D. Alt.	D.W.	Diff.	Obs. D. Alt.
$8^h\ 54^m\ 08^s\cdot8$	27·6	51° 40′	$9^h\ 02^m\ 50^s\cdot8$	28·4	54° 40′
8 54 36·4	28·0	51 50	9 03 19·2	28·0	54 30
8 55 04·4	27·6	52 00	9 03 47·2	29·2	54 20
8 55 32·0	27·6	52 10	9 04 16·4	27·6	54 10
8 55 59·6	28·0	52 20	9 04 44·4	28·4	54 00
8 56 27·6	27·6	52 30	9 05 12·4	28·4	53 50
8 56 55·2		52 40	9 05 40·8		53 40
7/38 44·0			7/29 51·2		
8 55 32·0		52 10	9 04 15·89		54 10

M.T.P.	$6^h\ 45^m$	April 29th
Long.	9 49 $21^s\cdot87$ (E,)	
G.D.	20 56	April 28th

Spica (E.).

D.W.	-	$8^h\ 55^m\ 32^s$
Slow	-	11 53
G.M.T.	-	20 48 32 approx.

		R.A.
Obs. D.alt.	52° 10′ 00″	
I.E.	+1 10	$13^h\ 20^m\ 42^s\cdot03$
	52 11 10	
C.E.	+40	Dec.
	2/52 11 50	10° 43′ 03″·8 S.
	26 05 55	
Mn. Ref.	−1 59	R.A.M.S.
	26 03 56	$2^h\ 22^m 27^s\cdot18$
Cor.	−3	For 20^h 3 17·13
		,, 48^m 7·88
	26 03 53	,, 32^s ·09
z	63 56 07	2 25 52·28

L.	42° 53′ 22″ S.	L sec.	0·13509
D.	10 43 04 S.	L sec.	0·00764
	32 10 18		
z	63 56 07		
	96 06 25	$\frac{1}{2}L$ hav	4·871438
	31 45 49	$\frac{1}{2}L$ hav	4·437168
		L hav H.	9·451336

H.	-	$19^h 43^m 02^s\cdot08$
R.A.	-	13 20 42·03
		33 03 44·11
R.A.M.S.	-	2 25 52·28
M.T.P.	-	6 37 51·83
Long.	-	9 49 21·87 (E.).
G.M.T.	-	20 48 29·96
D.W.	-	8 55 32·00
D.W. slow on G.M.T.		11 52 57·96
		11 52 57·77
		2/115·73
Mean error, slow	-	11 52 57·86

Rigel (W.).

D.W.	-	$9^h\ 04^m\ 15^s\cdot89$
Slow	-	11 53
G.M.T.	-	20 57 15·89 approx.

		R.A.
Obs. D.alt.	54° 10′ 00″	
I.E.	+1 10	$5^h\ 10^m\ 24^s\cdot39$
	54 11 10	
C.E.	+40	Dec.
	2/54 11 50	8° 17′ 58″· 2S.
	27 05 55	
Mn. Ref.	+1 54	R.A.M.S.
	27 04 01	$2^h 22^m\ 27^s\cdot18$
Cor.	−3	For 20^h 3 17·13
		,, 57^m 9·39
	27 03 58	,, 16^s ·04
z	62 56 02	2 25 53·74

L.	42° 53′ 22″ S.	L sec.	0·13509
D.	8 17 58 S.	L sec.	0·00457
	34 35 24		
z	62 56 02		
	97 31 26	$\frac{1}{2}L$ hav	4·876205
	28 20 38	$\frac{1}{2}L$ hav	4·388869
		L hav H.	9·404734

H.	-	$4^h 02^m 04^s\cdot88$
R.A.	-	5 10 24·39
		9 12 29·27
R.A.M.S.	-	2 25 53·74
M.T.P.	-	6 46 35·53
Long.	-	9 49 21·87 (E.)
G.M.T.	-	20 57 13·66
D.W.	-	9 04 15·89
D.W. slow on G.M.T.		11 52 57·77

The following comparisons were made :—

Before landing

A - -	7^h	31^m	00^s
D.W. -	7	26	12·8
D.W., slow	0	04	47·2 on *A*

After return

A -	10^h	11^m	00^s	*A* -	10^h	12^m	00^s	*A* -	10^h	12^m	30^s
D.W.	10	06	12	*B* -	7	11	31·5	*C* -	9	56	14
D.W. slow	0	04	48	*B* slow	3	00	28·5	*C* slow	0	16	16 on *A*

Change in comparison between D.W. and *A* is 0·8 second.

D.W. at 1st comparison - -	7^h	26^m	$12^s\cdot8$
„ 2nd „ - -	10	06	12
Elapsed time by D.W. - -	2	39	59·2 = 160^m.

D.W. at mid observation *Spica* -	8^h	55^m	$32^s\cdot0$
„ „ „ *Rigel* -	9	04	15·89
	2/17	59	47·89
Mean D.W. time of observation	8	58	53·94
D.W. at 2nd comparison - -	10	06	12
Elapsed time - - - - -	1	07	18·06 = $67^m\cdot3$.

$$\frac{67\cdot3 \times \cdot8}{160} = \cdot34^s$$

D.W. slow on *A* on return - - -	0^h	04^m	48^s
			$-\cdot34$
Mean comparison D.W. slow on *A* -	0	04	47·66
D.W. slow on G.M.T. - - - -	11	52	57·86
A slow on G.M.T. - - - -	11	48	10·20
B slow on *A* - - - - - - -	3	00	28·5
B slow on G.M.T. - - - -	2	48	38·70
A slow on G.M.T. - - - -	11	48	10·20
C slow on *A* - - - - - - -	0	16	16
C slow on G.M.T. - - - -	0	04	26·20

148. Errors involved in absolute altitudes :—

Absolute altitudes on one side of the meridian.—In this observation the following errors are involved :—Instrumental error, shade error, roof error, error due to irradiation, error due to abnormal refraction, and personal error.

Instrumental error.—This includes all unknown errors of the sextant, and its effect cannot be eliminated.

Shade error.—This is due to the fact that the two rays, from the horizon glass and artificial horizon, pass through different shades before reaching the eye, and these shades may have different errors. The possibility of shade error is avoided by using a dark eye-piece on the telescope, for both rays will then be affected in the same manner whatever may be the error of the eye-piece. For this reason a dark eye-piece should always be used when taking these observations in preference to the sextant shades.

Roof error.—This is due to lack of parallelism between the faces of the glass used in the roof of the artificial horizon, and may be eliminated by reversing the roof of the artificial horizon half way through the set of observations.

Error of irradiation.—This is due to an optical illusion, strongly illuminated objects on a dark ground appearing much larger than they really are. This error is eliminated by taking two sets of observations, one of the upper limb and one of the lower limb, working each separately and taking the mean of the results, and by using the darkest eye-piece through which the limb of the body can be clearly distinguished.

Error due to abnormal refraction.—This cannot be eliminated.

Personal error.—This is due to a peculiarity of habit of the observer and cannot be eliminated.

Mean of the results of absolute altitudes of the sun taken A.M. and P.M. — We have seen above that the instrumental error, and the error due to abnormal refraction, cannot be eliminated in absolute altitudes on one side of the meridian; if, however, absolute altitudes are taken on both sides of the meridian when the sun has about the same altitude, these errors to some extent cancel one another.

Mean of the results of absolute altitudes of stars taken East and West of the meridian.—The most accurate results are obtained from absolute altitudes of two stars, one East and the other West of the meridian and of about the same altitude, the interval between the observations being as brief as possible.

The effects of errors in this and in the preceding case are as follows:—

Instrumental error.—This has an approximately equal and opposite effect on the error of the deck watch obtained from the two observations, and therefore nearly disappears in the mean of the results.

Roof error.—When observations are taken on both sides of the meridian, it is unnecessary to reverse the roof of the artificial horizon half way through each set of observations ; but the observer should be careful to note that the mark on the roof is in the same relative position at each observation, *i.e.*, mark right or mark left at each observation.

Abnormal refraction.—This has an equal and opposite effect on the error of the deck watch at the two observations, provided that the atmospheric conditions have not changed. For this reason the second of the above two methods of obtaining the error of the chronometers is regarded as the more accurate.

Personal error.—The personal error cannot be eliminated.

149. Error of the chronometer by equal altitudes.—To ascertain the error of the chronometer as exactly as possible with sextant and artificial horizon, we must endeavour to get rid of the instrumental and other errors, and this is attained by observing at equal altitudes East and West of the meridian. It will be evident that whatever be the instrumental and other errors, supposing them to remain unaltered, the middle time between the observations will be the same ; for whatever tends to make the observed altitude more or less in the forenoon will act in the same manner in the afternoon, and as we do not want to know what that altitude is, but merely to ensure that it is the same A.M. and P.M., the amount of the errors is immaterial. The method of equal altitudes therefore should be used whenever we wish to get the error very exactly.

Equal altitudes of the sun can be taken either in the forenoon and afternoon of the same day so as to find the error at noon ; or in the afternoon of one day and the forenoon of the next to obtain the error at midnight. Theoretically these two are equally correct, but it is better to get the error at noon because in this case the elapsed time is less and gives less latitude to the chronometers and deck watches for eccentricity.

The principle of finding the error of chronometer by observation of equal altitudes is that, as the earth revolves at a uniform rate, equal altitudes of a body on either side of the meridian will be found at equal intervals from the time of the meridian passage of the body, and therefore the mean of the times of such equal altitudes gives the time of the meridian passage.

In the case of stars, the declinations are practically constant, so that this is strictly true, and the calculation of the error of a chronometer is confined to taking the difference between the mean of the times shown by the chronometer and the calculated time of the meridian passage (§ 125 (*b*)).

Thus, let t_1 be the time by the chronometer at the first observation, and t_2 the time at the second, then $\frac{t_1 + t_2}{2}$ is the chronometer time of the meridian passage of the body, which, compared with the true time of meridian passage (R.A. ✱ – R.A.M.S.) gives the error of the chronometer at the time of the meridian passage of the body.

In the case of the sun, however, the declination is constantly changing; the altitudes are thereby affected, and an altitude equal to that observed before meridian passage will be reached after meridian passage, sooner or later according to the direction of the change in declination.

It is therefore necessary to make a calculation of the correction resulting from the change in declination, to be applied to the middle time in order to reduce it to apparent noon. This correction is called the "equation of equal altitudes."

150. Formula for the equation of equal altitudes.—In Fig. 131, let X_1 and X_2 be the true places of the sun at the times of the A.M. and P.M. observations respectively, and let $(D + dp)$ and $(D - dp)$ be the declinations at those times, dp being the change of polar distance (or declination) in seconds of arc in half the elapsed time.

Let the celestial meridian PA bisect the angle X_1PX_2, then if t_1 and t_2 are the chronometer times at the two observations, the sun will be on the meridian PA when the chronometer time is $\frac{t_1 + t_2}{2}$, and therefore, if we apply the angle APS to the mean of the chronometer times, we obtain the chronometer time at which the sun is on the meridian of the observer. This angle APS is the equation of equal altitudes and will be denoted by e.

Let ZPX_3 be a triangle equal in all respects to ZPX_1, then since PS bisects the angle X_1PX_3 and PA bisects the angle X_1PX_2,

$$e = \tfrac{1}{2}\, X_2PX_3.$$

Let PX be a celestial meridian bisecting the angle X_2PX_3; let X_2X_3 be the arc of a small circle whose centre is Z and intersecting the celestial meridian PX in X, then

$$e = XPX_2 \text{ or } XPX_3.$$

Since PX is the mean value of PX_2 and PX_3, the declination of X is D, which is very nearly the declination of the sun at apparent Noon.

Let the parallel of declination through X intersect PX_2 in K; then, since the triangle XKX_2 is so small, it may be considered a plane triangle right-angled at K, and we have

$$\begin{aligned} e = XPX_2 &= XK \sec D = KX_2 \cot KXX_2 \sec D \\ &= KX_2 \tan ZXK \sec D \\ \therefore e &= dp \cot PXZ \sec D; \end{aligned}$$

or, if e is expressed in seconds of time

$$e = \frac{dp}{15} \cot PXZ \sec D.$$

Therefore the time shown by the chronometer at the instant when the sun is on the meridian of the observer is

$$\frac{t_1 + t_2}{2} + \frac{dp}{15} \cot PXZ \sec D \text{ (seconds).}$$

When applying the equation of equal altitudes to the mean of the chronometer times, care should be taken to give dp and cot PXZ their proper algebraical signs, dp being positive when the polar distance is increasing, and *vice versâ.*

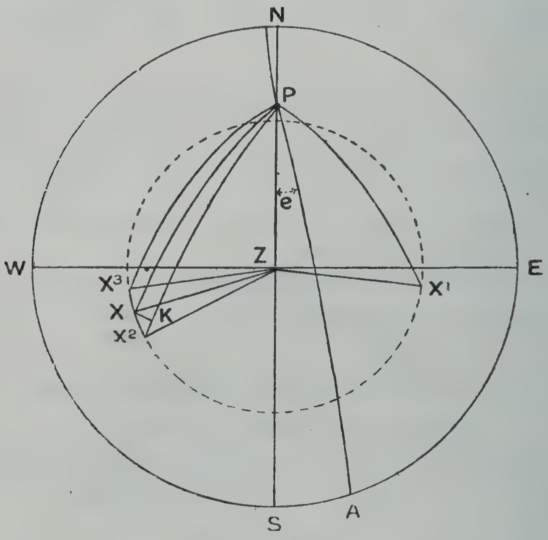


Fig. 131.

151. Errors involved in equal altitudes. — The effects of errors in this observation are the same as in the case of stars observed East and West of the meridian, except as regards the instrumental error, which has no effect provided that it has remained constant in the interval between the observations.

152. Example of error of chronometer by equal altitudes.—*Example*:—On April 28th, 1914, at Zanzibar, Lat. 6° 09′ 43″ S., Long. 39° 11′ 08″ E., the following observations of the sun were taken to determine the errors of the chronometers on G.M.T. :—

A.M.			P.M.		
D.W.	Diff.	Obs. alt. $\underline{\odot}$	D.W.	Diff.	Obs. alt. $\underline{\odot}$
$1^h\ 33^m\ 52^s{\cdot}8$	21·6	68° 10′	$8^h\ 28^m\ 54^s{\cdot}0$	21·6	69° 50′
1 34 14·4	21·6	68 20	8 29 15·6	22·0	69 40
1 34 36·0	22·0	68 30	8 29 37·6	21·2	69 30
1 34 58·0	21·2	68 40	8 29 58·8	21·6	69 20
1 35 19·2	22·0	68 50	8 30 20·4	21·6	69 10
1 35 41·2	21·2	69 00	8 30 42·0	21·2	69 00
1 36 02·4	21·6	69 10	8 31 03·2	22·0	68 50
1 36 24·0	21·6	69 20	8 31 25·2	21·2	68 40
1 36 45·6	22·0	69 30	8 31 46·4	22·0	68 30
1 37 07·6	21·2	69 40	8 32 08·4	21·6	68 20
1 37 28·8		69 50	8 32 30·0		68 10
11/392 30·0			11/337 41·6		
1 35 40·91			8 30 41·96		

Comparisons A.M. :—

Before landing—

A - - $4^h\ 33^m\ 00^s$
D.W. - 0 27 49·2

D.W. slow - 4 05 10·8 on *A*

After returning—

A - - $6^h\ 47^m\ 00^s$
D.W. - 2 41 50·4

D.W. slow - 4 05 09·6 on *A*

Change in comparisons between D.W. and *A* is 1·2 seconds.

D.W. at first comparison - - $0^h\ 27^m\ 49^s{\cdot}2$
D.W. at second comparison - 2 41 50·4

Elapsed time by D.W. - - 2 14 01·2 = 134^m

D.W. at mid observation - - $1^h\ 35^m\ 40^s{\cdot}91$
D.W. at 2nd comparison - - 2 41 50·4

Elapsed time by D.W. - - 1 06 09·49 = $66^m{\cdot}1$

$$\frac{66\cdot1\times1\cdot2}{134} = \cdot59^s$$

D.W. slow on *A* on return - $4^h\ 05^m\ 09^s{\cdot}6$
·59

Mean comparison A.M. D.W. slow 4 05 10·19 on *A*
D.W. at mid observation - - 1 35 40·91

Mid observation by *A* - - 5 40 51·1

Comparisons at apparent noon :—

A -	$9^h\ 09^m\ 00^s$	*A* -	$9^h\ 10^m\ 00^s$	*A* -	$9^h\ 10^m\ 30^s$
D.W.	5 03 51·8	*B* -	7 11 46·5	*C* -	6 05 29·0
Slow	4 05 08·2	Slow	1 58 13·5	Slow	3 05 01·0 on *A*

Comparisons P.M. :—

Before landing—

A - $11^h\ 31^m\ 00^s$
D.W. 7 25 53·2

D.W. slow 4 05 06·8 on *A*

After returning—

A - - $1^h\ 46^m\ 00^s$
D.W. - 9 40 54·8

D.W. slow 4 05 05·2 on *A*

Change in comparisons between D.W. and *A* is 1·6 seconds.

D.W. at 1st comparison - - $7^h\ 25^m\ 53^s$·2
D.W. at 2nd comparison - - 9 40 54 ·8

Elapsed time by D.W. - - 2 15 01 ·6 = 135^m

D.W. at mid observation - - $8^h\ 30^m\ 41^s$·96
D.W. at 2nd comparison - - 9 40 54·8

Elapsed time by D.W. - - 1 10 12·84 = 70^m·2

$$\frac{70·2 \times 1·6}{135} = ·83^s$$

D.W. slow on *A* on return - - - $4^h\ 05^m\ 05^s$·2
·83

Mean comparison P.M., D.W. slow - 4 05 06·03 on *A*
D.W. at mid. observation - - - 8 30 41·96

Mid. observation by *A* - - - - 0 35 47·99

A.T.P. -	$24^h\ 00^m\ 00^s$ Apl. 27th.	Dec.	$13°\ 58'\ 21''$·1 N.	47·60
Long. -	2 36 44·53 (E.)		— 2 06·1	2·65
G.A.T. -	21 23 15·47		13 56 15 N.	23800
Eq. T. (appx.)	— 2			28560
				9520
G.D. -	21 21 Apl. 27th			60/126·1400
				2′ 06″·1
G.A.T. -	$21^h\ 23^m\ 15^s$·47	Eq. T.	$2^m\ 28^s$·07 — to A.T.	·388
Eq. T. -	— 2 27·04		— 1 ·03	2·65
G.M.T. -	21 20 48·43			1940
			2 27·04 — to A.T.	2328
				1776
				1·02820

Mid. observations A.M. by *A* $5^h\ 40^m\ 51^s$·10
Mid. observations P.M. by *A* 12 35 47 ·99

Elapsed time by *A* 2/6 54 56 ·89

½ elapsed time by *A* 3 27 28 ·44 = 3^h·45

To find the angle *PXZ*—

ZPX	$3^{h}\ 27^{m}\ 28^{s}{\cdot}44$	*L* hav	9·28161
L	6° 09′ 43″ S.	*L* cos	9·99748
D	13 56 15 N.	*L* cos	9·98702
$(L + D)$	20 05 58	*L* hav θ	9·26611
		Nat hav θ	·18455
		Nat hav $(L + D)$	·03045
		Nat hav *ZX*	·21500
			ZX = 55° 15′

ZX	55° 15′ 00″	*L* cosec	0·08531
PX	103 56 15	*L* cosec	0·01298
	48 41 15		
PZ	83 50 17		
	132 31 32	½*L* hav	4·96160
	35 09 02	½*L* hav	4·47994
		L hav *PXZ*	9·53983
		PXZ =	72° 08′ 00″

To find the equations of equal altitudes—

$$e = \frac{dp}{15} \cot PXZ \sec D.$$

Hourly change in declination	47″·60	log	1·67761
½ elapsed time	$3^{h}{\cdot}45$	log	·53782
PXZ	72° 08′ 00″	*L* cot	9·50833
D	13° 56′ 15″	*L* sec	·01298
			1·73674
	15	log	1·17609
		log *e*	·56065
			$e = + 3^{s}{\cdot}64$

the + sign is given because *dp* is + and cot *PXZ* is +.

Mid observation A.M. by *A*	$5^{h}\ 40^{m}\ 51^{s}{\cdot}10$
Mid observation P.M. by *A*	12 35 47 ·99
	2/18 16 39 ·09
Mean of chronometer times	9 08 19 ·54
Equation of equal alts.	+ 3 ·64
A chronometer at noon (A.T.P.)	9 08 23 ·18
G.M.T. at noon (A.T.P.)	21 20 48 ·43
A slow on G.M.T. at noon (A.T.P.)	0 12 25 ·25
B slow on *A*	1 58 13 ·50
B slow on G.M.T. at noon (A.T.P.)	2 10 38 ·75
A slow on G.M.T. at noon (A.T.P.)	0 12 25 ·25
C slow on *A*	3 05 01 ·00
C slow on G.M.T. at noon (A.T.P.)	3 17 26 ·25

When taking equal altitudes it is necessary to determine at what time by the ship's clocks the second set of observations should be taken. In the preceding example it is required to find at what time (S.M.T.) the observer should have been ready to take the P.M. set of observations.

D.W. of last observation A.M.	1^{h}	38^{m}	
Slow on G.M.T. (approx.)	4	18	
G.M.T. of last observation A.M.	5	56	
Long.	2	37	(E.)
S.M.T. of last observation A.M.	8	33	
Eq. T.		+2	
S.A.T. of last observation A.M.	8	35	
	12	00	
S.A.T. of 1st observation P.M.	3	25	
Eq. T.		−2	
S.M.T. of 1st observation P.M.	3	23	

Therefore the observer should have been ready by about 3^{h} 15^{m} P.M.

153. Summary of necessary comparisons.—The following comparisons are necessary when taking observations on shore for finding the errors of the chronometers.

For sun equal altitudes:—

(1) Before landing A.M., between D.W. and *A* chronometer.
(2) After returning A.M., between D.W. and *A* chronometer.
(3) At apparent noon compare all chronometers and deck watch with *A* chronometer.
(4) Before landing P.M., between D.W. and *A* chronometer.
(5) After returning P.M., between D.W. and *A* chronometer.

The 1st, 2nd, 4th, and 5th comparisons are necessary to obtain the mean comparison in the forenoon and afternoon. The 3rd comparison is required because equal altitudes give the error at apparent noon.

If observations are taken P.M. on one day and A.M. on the next, the 3rd comparison should be made at apparent midnight.

For absolute altitudes on both sides of the meridian.—The same comparisons are required as for equal altitudes.

For absolute altitudes on one side of the meridian.—

(1) Before landing, between D.W. and *A* chronometer.
(2) After returning, between D.W. and *A* chronometer; the *A* chronometer should also be compared with the others.

For absolute altitudes of stars East and West of the meridian.—The same comparisons are required as for absolute altitudes on one side of the meridian.

154. Notes on observations for error of chronometer.—The sun or heavenly body selected should fulfil the following conditions:—

(*a*) It should be of sufficient altitude to be visible in the artificial horizon, that is, above 15° with the instruments usually supplied.
(*b*) The altitude should not be greater than about 60° in order that the double altitude may go conveniently on the limb of the sextant.
(*c*) The motion in altitude should be sufficiently fast for the time to be noted very exactly.

To determine the speed of a body in altitude at any instant, let X and Y be the true places of a heavenly body when its hour angles are H and $(H + dH)$ respectively, Fig. 132.

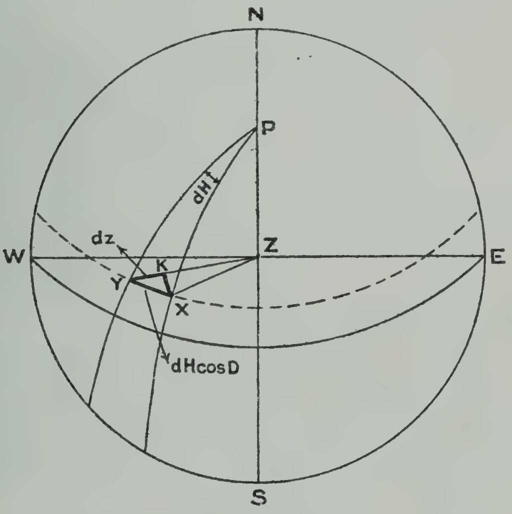


Fig. 132.

Then $XY = dH \cos D$. Let XK be the arc of a small circle described with Z as centre, then YK is the change of altitude for the change of hour angle dH.

The triangle YXK, being small, may be regarded as a plane triangle right-angled at K; therefore, denoting the change of altitude by dz, we have

$$\begin{aligned} dz &= XY \sin KXY \\ &= XY \cos PXK \\ &= XY \sin PXZ \\ &= XY \frac{\cos L \sin A}{\cos D}, \end{aligned}$$

where A is the azimuth of the body.

$$\therefore dz = dH \cos D \frac{\cos L \sin A}{\cos D}$$
$$= dH \cos L \sin A.$$

Therefore if dH is expressed in seconds of time and dz in minutes of arc we have

$$\frac{dz}{dH} = \frac{\cos L \sin A}{4}$$

This is the speed of the body in altitude, expressed in minutes of arc per second of time.

When the altitude of a heavenly body changes 5′ (10′ of double altitude on the sextant) in 35 seconds of time, that is when the speed is $\frac{1'}{7^{s}}$, satisfactory results are obtained, and when there is any choice, observations of bodies whose speed is less than this should not be taken. Therefore, from the formula, we have

$$\frac{\cos L \sin A}{4} \text{ is not less than } \frac{1}{7},$$

or

$$\sin A \text{ is not less than } \frac{4}{7} \sec L.$$

To summarise these three conditions:—The altitude of the body should lie between 15° and 60°, and if A is the azimuth of the body, A should be as nearly 90° as possible, and in no case should sin A be less than $\frac{4}{7}$ sec L.

In the winter in moderately high latitudes the sun will not fulfil the conditions above, but stars can always be found which will more nearly do so. In England and corresponding latitudes the sun is useless for some months, and at midwinter its altitude is so small that it cannot be observed in the artificial horizon even when on the meridian.

In Inman's Tables there is a table which gives the hours, depending on the latitude and declination, between which it is possible to take observations of the sun in an artificial horizon for error of chronometer, having regard to the conditions stated above.

When about to take observations, select a place remote from traffic and sheltered as far as possible from the wind; the ground should be solid or the mercury will tremble; avoid artificially made ground. If possible use the observation spot given on the chart; if not, fix your position by sextant angles and station pointer, plot it on the chart, and then measure off its exact latitude and longitude.

When selecting a place for observations on both sides of the meridian, do not go so close to buildings, trees, or hills which may obscure the body when at the required altitude on the other side of the meridian.

See that the horizon trough is clean and free from dust; place it in the direction of its shadow (if using the sun), and put the roof over it except at one end. Remove the cover and screw-plug from the mercury bottle and screw the cover on again; put a finger on the hole, invert the bottle and keep it in this position for a time so as to allow the scum and impurities to rise through the mercury; then fill the trough, but do not pour in all the mercury or the scum will flow in also and cloud the surface; then put the roof on properly.

When packing up a mercurial artificial horizon, put the mercury bottle in the wooden box before lifting up and emptying the trough; if any mercury is spilled, it is then caught in the box and can be recovered.

Before taking observations remove any existing side error (Part IV., Chapter XXVIII.) from the sextant, and take and record the index error. If taking index error on any occasion when the sun is low, measure the diameter between the right and left limbs, and not between the upper and lower limbs, on account of refraction.

For the sun use the inverting telescope with the highest power eye-piece; the bigger the sun's images appear in the telescope the better can a contact of the limbs be observed. The loss of light due to a high power is of no importance.

Bring the images together roughly before screwing in the telescope, and see that the tangent screw has been run back in the right direction. The image which moves in the field of view when the index bar is moved is the reflected image; if this is above the direct image when using the inverting telescope, you will be observing the upper limb, and if below, the lower limb, whether the body is rising or setting.

Take sets of upper limbs and sets of lower limbs alternately and take an equal number of sets of each; this obviates the effect of irradiation (§ 148). Seven, nine, or eleven is a good number of observations to take in a set.

At the end of each set of observations look at the deck watch and see that the right minute has been written down.

Twilight is the best time to observe stars if suitable stars can be found; for if it is dark a lantern or light is required by the time-taker, and this is liable to disturb the observer's vision.

When getting a star down it is best to approach very close to the artificial horizon, as there is then less chance of observing the wrong star. It is often useful to calculate what the altitude of the star will be and to set twice that altitude on the sextant.

A star has no appreciable diameter, and the contact occurs when the reflected and direct images flick across one another.

The surface of the mercury in the artificial horizon is perfectly horizontal at any place where the direction of gravity (the plumb line) is normal to the earth's surface at that place. In the immediate neighbourhood of mountains the direction of gravity slightly deviates from the vertical, and the surface of the mercury is consequently not truly horizontal ; therefore such a locality should be avoided when observations with the artificial horizon are required.

155. The rate of the chronometer.—As regards the rate of the chronometer, it would at first appear that it is only necessary to obtain errors at the same time on two successive days, and that the difference between these errors would be the daily rate. This would be so if we were able to guarantee that the errors found were exactly correct, but as each may be inaccurate by some small amount, it is obvious that the resulting rate would be vitiated by the sum or difference of the inaccuracies in the errors.

For this reason we obtain the errors at an interval of some days, and the resulting rate will then only be in error by

$$\frac{\text{the sum or difference of the inaccuracies of the observed errors}}{\text{number of days.}}$$

Thus it appears that to obtain the rate as accurately as possible the interval between the observations should be large. This would be true if the chronometer were always to maintain a steady rate, but the rate of a chronometer seldom remains steady for many days together ; it varies with change of temperature, and is often different according as the ship is at sea or in harbour.

Taking the above into consideration, it is generally accepted that the interval between observations for error of chronometer, in order to obtain the rate, should not be less than six days or more than ten days.

To obtain the rate as accurately as possible, the observations should be taken in such a manner that the sum or difference of the inaccuracies in the observed errors is as small as possible. It is obvious that, if the inaccuracy of each error is in the same direction, the resulting rate will be in error by

$$\frac{\text{the difference of the inaccuracies in the observed errors}}{\text{number of days,}}$$

and the observations should therefore be taken in such a manner that the inaccuracies are likely to be in the same direction.

For this reason, the two observations for a rate should always, if possible, be of the same nature, and it would be imprudent to obtain the rate from the difference of the errors obtained by absolute altitudes A.M. on one day and absolute altitudes P.M. on another day, for in such a case the rate would probably be in error by

$$\frac{\text{the sum of the inaccuracies in the observed errors}}{\text{number of days.}}$$

To illustrate the above, suppose that the error of the chronometer was found from absolute altitudes A.M. on March 3rd, and that equal altitudes of the sun were observed on March 10th.

The error of the chronometer on March 10th was found in the ordinary way from the equal altitudes, but the rate was found from the difference between the error calculated from the absolute altitude taken on March 3rd, and the error found by working the A.M. set of observations taken on March 10th as absolute altitudes.

It is important that the interval between the observations, often called the epoch, and expressed in days, should be determined as accurately as possible. When observations are taken at different places, it should be remembered that the difference of longitude is involved, and consequently it should always be made a practice to find the epoch from the Greenwich dates, thus :—

Epoch = G.D. 2nd observation − G.D. 1st observation.

Example:—On March 3rd, 1914, at about $6^h\ 45^m$ P.M. (M.T.P. nearly) at Yokohama, Long. 139° 39′ 13″ E., a chronometer was found to be slow on G.M.T. $3^h\ 14^m\ 57^s{\cdot}34$ (from observations of stars E. and W. of the meridian).

On March 11th, 1914, at about $6^h\ 15.^m$ A.M. (M.T.P. nearly), at Honolulu, Long. 157° 51′ 53″ W., the chronometer was found to be slow on G.M.T. $3^h\ 15^m\ 14^s{\cdot}71$ (from similar observations).

Required the rate of the chronometer.

	1st error.			*2nd error.*	
M.T.P.	$6^h\ 45^m$	Mar. 3rd.	M.T.P.	$18^h\ 15^m$	Mar. 10th.
Long.	$9\ 18\ 36^s{\cdot}9$	(E.)	Long.	$10\ 31\ 27^s{\cdot}5$	(W.)
G.D.	21 26	Mar. 2nd.		28 46	Mar. 10th.
				24 00	
			G.D.	4 46	Mar. 11th.

G.D. at 2nd Obs'n	$11^d\ 04^h\ 46^m$	Error at 2nd Ob'sn.	$3^h\ 15^m\ 14^s{\cdot}71$
G.D. at 1st Obs'n	2 21 26	Error at 1st Ob'sn.	3 14 57 ·34
Epoch - -	8 07 20	Accumulated rate	17·37
	= 8·306 days		

$$\text{Daily rate} = \frac{17{\cdot}37}{8{\cdot}306} = 2{\cdot}091 \text{ seconds losing.}$$

PART II.—PILOTAGE

CHAPTER XVII.

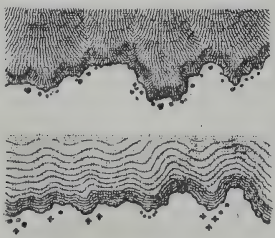
THE ADMIRALTY CHART AND ARTIFICIAL AIDS TO NAVIGATION.

156. Coasts.—In Part I. navigation has been treated without special reference to dangers, such as rocks, shoals, &c.; that part of navigation which is particularly concerned with the conduct of the ship when in the neighbourhood of such dangers is called pilotage, and will be dealt with in the two chapters comprising this part of the book.

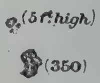
To conduct a ship in the neighbourhood of dangers, that is to pilot a ship, necessitates a knowledge of the coasts, dangers, and artificial aids to navigation such as buoys, lights, and fog signals.

The coasts of countries take various forms; a coast may consist of vertical cliffs with deep water adjacent to them so that the coast line is very sharply defined, or it may be low with the adjacent water very shallow and the coast line indefinite. Between these two extreme forms there are many others too numerous to mention.

On approaching land it is important to be able to recognise the coast which may come into view. To facilitate this, the nature of the coast and the prominent features of the adjacent land are indicated on the chart by a system of conventional signs and abbreviations, as shown below:—



Steep coast.



Islands and Rocks.

The figures within brackets express the heights in feet above the level of high water of an ordinary spring tide, or above the level of the sea in cases where there is no tide.

ppen, in particular, when the generator is at one end of an iron or steel bulkhead or beam and the compass at the other end. The generator should as a rule be installed as far as conveniently possible from the compass and the compass should be watched and checked in order to ascertain whether the deviation is being in any way affected. *July 1923.*

PILOTS.

PILOTS.—*Caution.*—In view of the danger and difficulty often attending the shipping and discharging of Pilots in exposed positions, the attention of Masters is directed to the necessity of obser. every precaution in manœuvring their ships when a Pilot is either boarding or leaving, especially in cases where a vessel is in ballast and strong winds are prevailing. The Master or Officer in charge of the bridge should take care to satisfy himself, on dropping the Pilot, that the latter is well clear of the ship and particularly of the counter before the propeller is moved. *June 1912.*

WRECK SYMBOLS ON CHARTS.

The following additional definition regarding sunken wreck symbols shown on the Admiralty charts, has now been adopted to obviate the use of the dangerous symbol, which hitherto has been the only symbol applicable in the case of non-dangerous wrecks lying in less than 10 fms. (18^m3).

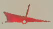
Signification.	Symbol.	
"*A wreck lying in depths of less than 10 fathoms (18^m3), which is not a danger to surface navigation, but over which the exact depth is unknown*"	+++	*Wreck* (*year*)

This definition will be added to the existing definition of the above symbol in the next edition of chart No. D.11 "Signs and Abbreviations." The remaining wreck symbols in use are as shown on the latest edition of this chart dated 18th June 1923 [Small Corrections 1925-*1650*]. *July, 1926.*

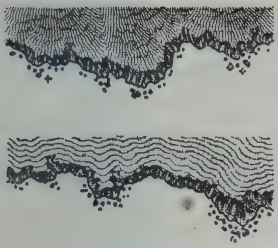
N to M N° 1014/1926.

To accompany Admiralty Notice to Mariners N? 2231 of 1927.

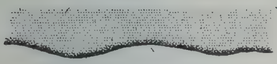
Wrecks

Stranded Wreck	*Wreck showing any portion of the hull or superstructure above Low Water.*	
Wreck of known depth	*Wreck over which the exact depth at Low Water is known.*	(5¼) *Wreck*
Dangerous Wreck	*Wreck over which the exact depth of water is unknown but which is considered dangerous to surface navigation.*	(+++)
Non-dangerous Wreck	*Wreck over which the exact depth is unknown but which is not considered dangerous to surface vessels capable of navigating in the vicinity*	-+++-
Remains of Wreck	*Remains of a Wreck no longer dangerous to surface navigation, but to be avoided by vessels anchoring, trawling, etc.*	◌ *Foul*
Old Symbol	*Partially or wholly submerged wreck where depth over is unknown.*	*Wreck*

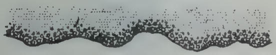
Note :– On the largest scale charts affected the year date of the wreck, if known, will be inserted if space permits



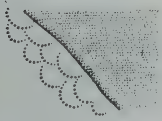
Cliffs.



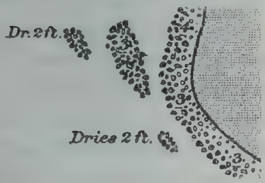
Sandy shore.



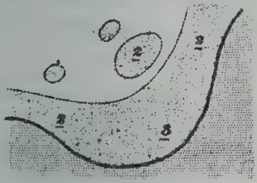
Stony or shingly shore.



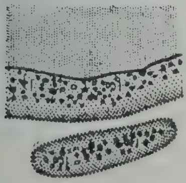
Breakers along a shore.



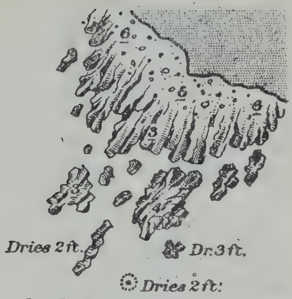
Stones, shingle, or gravel, dry at low water of ordinary spring tides.



Mud banks, dry at low water of ordinary spring tides.

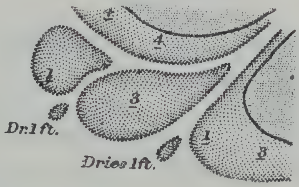


Sand and gravel, or stones, dry at low water of ordinary spring tides.

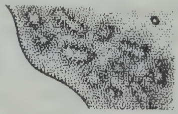


Rocky ledges and isolated rocks, dry at low water of ordinary spring tides.

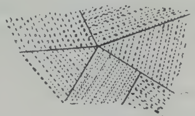
The underlined figures, on the rocks which uncover, express the heights in feet above the level of low water of ordinary spring tides unless otherwise stated.



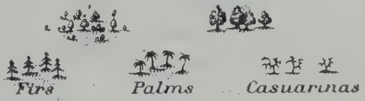
Sandy beach and banks, dry at low water of ordinary spring tides.



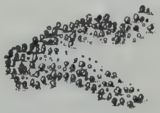
Sand hills or dunes.



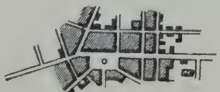
Cultivated land.



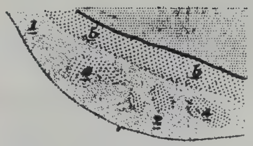
Trees.



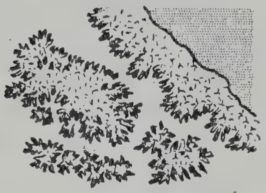
Mangroves.



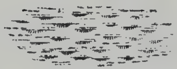
Towns, villages, or houses.



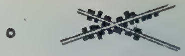
Sand and mud, dry at low water of ordinary spring tides.



Coral reefs.

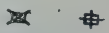


Swampy, marshy, or mossy land.



Villages or houses.

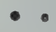
Churches or chapels.



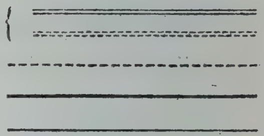
Temples.

Windmills.

Triangulation Station.



Beacon, chimney, flagstaff, or other fixed point.

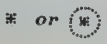


Roads
Track or Footpath
Railway
Tramway

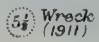
The configuration of the land is shown on the charts by the heights of various points, the heights of the summits of prominent hills and other elevated points being shown by figures within brackets. Heights given on the charts are those above the level of high water of ordinary spring tides, unless otherwise stated in the title of the chart. On some charts the configuration of the land is delineated by means of contour lines, which are lines drawn through all points of the same height on the same undulation. These lines are drawn for various heights, the difference between any two consecutive lines being the same, so that the proximity or otherwise of the contour lines indicates at a glance the slope of the land.

Views of prominent points, entrances to harbours, &c., are shown on some charts; the positions from which the views are taken are also shown. Views are shown in Fig. 142, Chapter XVIII. (page 251).

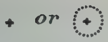
157. Dangers.—In the vicinity of coasts (and sometimes at a considerable distance from them) small isolated rocks frequently exist, some of which are well above the surface of the sea while others are just below it, or at one time above and at another time below it according to the state of the tide. An indication of submerged rocks is sometimes given by the presence of kelp or seaweed on the surface of the water. Rocks and dangers, with the floating beacons, &c., which sometimes mark them, and reported dangers, called vigias, are shown on the charts by means of the following conventional signs and abbreviations:—



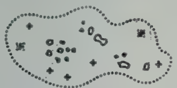
Rock awash at low water of ordinary spring tides.



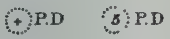
Wreck, the depth over which is known.



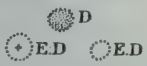
Rock with less than six feet of water over it at low water of ordinary spring tides.
On small scale charts this symbol is used for rocks with greater depths of water over them.



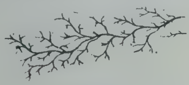
Rocks with limiting danger lines.



Rock or shoal, the position of which is doubtful.

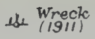


Reported rock or shoal, the existence of which is doubtful.

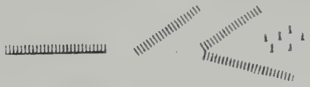


Kelp.

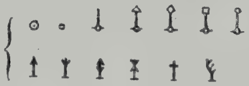
See N to M No 1014/26, and No 2231/27



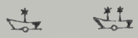
Wreck, partially or wholly submerged, the depth over which is unknown.



Fishing stakes.



Fixed or floating beacons.



Light vessels or floats.

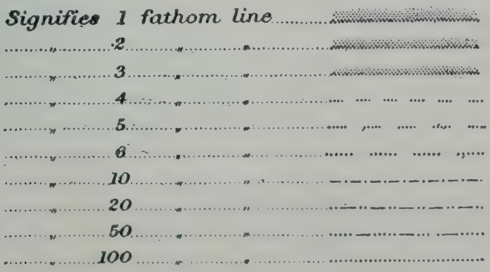
The actual position of a floating beacon or light vessel is the centre of the water line as depicted on the chart, and is often marked by a small circle.

158. Depth of water.—The depth of the water at any spot, as found from the soundings taken at the time of the survey, is indicated by a number which shows the depth in feet or fathoms (as stated in the title of the chart) when the level of the surface of the water is at a certain height. This level or datum is that of the surface of the water at low water of ordinary spring tides, unless otherwise stated in the title of the chart.

A bench mark is a mark on a dock wall, or in some convenient position, to the level of which the datum of the soundings may be referred in case of necessity.

When a sounding is taken and the bottom is not reached by the lead the depth to which the lead actually descends is shown thus $\overline{\dot{70}}$, $\overline{\dot{100}}$, which indicates that the bottom was not reached at depths of 70 fathoms and 100 fathoms respectively.

If a line is drawn on the chart through all points at which the depth is the same, the line is called a fathom line. Fathom lines for different depths are indicated on the chart as shown below.



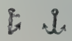
159. Quality of the bottom.—The quality of the bottom at any spot, as found when soundings were taken, is printed in an abbreviated form below the number which indicates the depth at that spot; the abbreviations for the various qualities of the bottom are shown below :—

QUALITY OF THE BOTTOM.

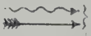
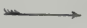
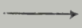
b	... blue	gy	... grey	s	... sand
blk	... black			sc	... scoriæ
br	... brown	h	... hard	sft	... soft
brk	... broken			sh	... shell
		l	... large	shin	... shingle
c	... coarse	lv	... lava	sm	... small
cal	... calcareous	lt	... light	sp	... sponge
chk	... chalk			spk	... specks, speckled
choc	... chocolate	m	... mud		
cin	... cinders	mad	... madrepore	st	... stones
cl	... clay	man	... manganese	stf	... stiff
crl	... coral	ml	... marl	stk	... sticky
		mus	... mussels		
d	... dark			t	... tufa
di	... diatom	oys	... oysters		
		oz	... ooze	vol	... volcanic
f	... fine				
for	... foraminifera	peb	... pebbles	w	... white
		pt	... pteropod	wd	... weed
g	... gravel	pum	... pumice		
gl	... globigerina			y	... yellow
gn	... green	r	... rock		
grd	... ground	rad	... radiolaria		

The quality of the bottom, as indicated by the arming of the lead when a sounding has been taken, may be of considerable value in estimating a ship's position.

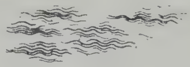
When a spot is to be selected at which to anchor a ship consideration should be given to the quality of the bottom as shown by the abbreviations on the chart; thus it is inadvisable to anchor a ship where the bottom is shown as rocky or hard, because of the risk of breaking the anchor, or of the anchor not obtaining a firm hold on the bottom. Good holding ground such as mud, clay, or sand should be selected when possible. On many charts the most suitable places for anchoring large and small vessels are shown by means of the following signs :—

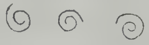
Anchorage for large vessels ... ...
,, ,, small ,, ... 

160. Tides and tidal streams. Currents.—Full information regarding these matters is given in Part III. The following abbreviations are used on the Admiralty charts :—

Equin^{l}	Equinoctial.	m.	minutes.
Fl. or fl.	Flood.	Np	Neap Tides.
H.W.	High Water.	ord.	ordinary.
H.W.O.S.	High Water of Ordinary Spring Tides.	Q^{r}.	Quarter.
h.	hour, hours.	Sp. or Spr.	Spring Tides.
kn.	knot, knots.		Current.
L.W.	Low Water.		Flood Tide Stream.
L.W.O.S.	Low Water of Ordinary Spring Tides.		Ebb Tide Stream.

H.W. or L.W. always refers to High Water or Low Water of Ordinary Spring Tides, unless otherwise stated.

Overfalls and Tide Rips ... ... 

Eddies ... ... 

161. General abbreviations.—Besides the abbreviations which have been enumerated above there are a number of others, of a general character, which are given on the charts as shown below :—

GENERAL ABBREVIATIONS.

A. (Agios)	Saint (Greek)
ab^{t}.	about
Anch^{e}.	Anchorage
Anc^{t}.	Ancient
Approx.	Approximate
Arch^{o}.	Archipelago
B.	Bay, Black
B. (Basse)	Shoal (French)
B^{a}. (Bana)	Cape or point (Japanese)
Bat^{y}.	Battery
B^{g}. (Berg)	Mountains (German) Cape (Dutch)
B^{k}, B^{ks}.	Bank, Banks
B.M.(↑)	Bench Mark
B^{n}., B^{ns}.	Beacon, Beacons
Bo. (Bogha)	Sunken Rock (Gaelic)
B^{r}. (Besar)	Great (Malay)
Br.	Bridge
B^{t}. (Bukit)	Hill (Malay)
C.	Cape
Cas.	Castle
Cath.	Cathedral
C.G.	Coast Guard
Ch.	Church or Chapel
Chan.	Channel
Ch^{y}.	Chimney
Conspic.	Conspicuous
Cov.	Covers, Covered
Cr.	Creek
D.	Doubtful
dist.	distant
Dr., dr.	Dries
E.,E^{n}. Eil^{n}. (Eilean)	Island, Islands (Gaelic)
E.D.	Existence doubtful
Ens^{a} (Ensenada)	Bay or Creek (Spanish)
Estab^{t}.	Establishment
Est^{o}.(Estero)	Estuary (Spanish)
F. (Fiume)	River (Italian)
F^{d}.	Fiord (Norwegian)
Fl. (Flu.)	Sunken Rock (Norwegian)

Fl^{ne}. (Fluene) Sunken Rocks (Norwegian)
F^{m}., F^{ms}. ..Fathom, Fathoms
F.S. ....Flagstaff
f^{t}., ft. ......foot or feet
F^{t}. ....Fort
G. ....Gulf
G^{a}. (Gawa) River (Japanese)
G^{d}., G^{de}. (Grand) Great (French)
G^{g} (Gunong) Mountain (Malay)
(Gusong) Shoal (Malay)
Gov^{t}. ......Government
Gr^{d}. (Grund) Shoal (German), (Norwegian)
G^{t}., Gr^{t}. ...Great
G.T.S. Great Trigonometrical Survey Station (India)
h. hrs. .....hour, hours
H^{a}. (Hana) Point (Japanese)
H^{d}. ....Head
H^{m}. (Holm) Island
H^{ne}. (Holmene) Islands (Norwegian)
H^{n}. ....Haven
Ho. ....House
H^{r}. ....Harbour, Higher
I., I^{t}., ...Island, Islet
I^{s}. ....Islands, Islets
in. ....Inches.
J., Jeb. (Jebel) Mountain (Arabic)
J^{a}. (Jima) Island (Japanese)
Jez^{t}. (Jezirat) Island (Arabic)
K^{g}. (Kampong) Village (Malay)
K^{g}. (Karang) Coral Reef (Malay)
K^{l}. (Kechil) Small (Malay)
L. ......Lake, Lock, Lough
L. (Lilla) }
Lit. ...... } Little (Norwegian)
L. ......
L^{a}. .... } ...Lagoon
Lag^{n}. ..
Lat. ......Latitude
L.B. ......Life Boat
L.B.S. ..... .Life Boat Station
L^{dg}. Leading (Lights or Beacons)
Landing (Place)

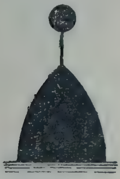
L^{e}., L^{es}. ...Ledge, Ledges
Long. ......Longitude
L^{r}. ....Lower
L.S.S. ......Life Saving Station
L^{t}. Ho. ...Lighthouse
L^{t}. Ves. ...Light vessel
m. ....miles, minutes
min. ......minutes
Mag. ......Magnetic
Mag^{z} ......Magazine
Mid. ......Middle
Mon^{t}. ......Monument
Mon^{y}. ......Monastery
M^{t}., M^{te}. ...Mountain
Mth. ......Mouth
N^{o}. ....Number
Obs^{n}. Spot + Observation Spot
Obs^{y}. ......Observatory
Occas^{l}. ...Occasional
Off. ....Office
Ord. ......Ordinary
P., P^{to}. ...Port, Porto, Puerto
Pag. ......Pagoda
Pass. ......Passage
P.D. ......Position doubtful
Pen^{la}. ......Peninsula
P^{k}. ....Peak
P^{o}. (Pulo) Island (Malay)
P.O. ......Post Office
Pos^{n}. ......Position
Prom^{y}. ...Promontory
Prov^{l}. ......Provisional
P^{t}., P^{ta}., P^{te}. Point
P. A. ...Position approximate
R. ....River
R.C. ......Roman Catholic
R^{f}. ....Reef
R^{d}., R^{ds}. ...Road, Roads
Rem^{ble}. ...Remarkable
R^{k}., R^{ks}. Rock, Rocks
R.S. ......Rocket Station
Ru. (Rudha) Point (Gaelic)
Ru. ....Ruin
R^{y}. ....Railway
s. ....seconds
S., S^{n}., S^{o}. ... }
S^{t}., S^{ta}., S^{to}. ... } Saint
S^{a}. (Sima or Shima) Island (Japanese)
(Serra or Sierra) Mountains (Spanish)

S^{d}..............Sound
Sem. ......Semaphore
S.B. ....Submarine Bell
Sg., Sg^{r}. (Sgeir) Rock, Rocks (Gaelic)
Sh............Shoal
S^{i}. { (Sidi) Tomb (Arabic)
(Sungi) River (Malay)
(Saki) Cape or Point (Japanese)
Sig..........Signal
Sk^{ne}. (Skierene) Rocks (Norwegian)
Sk^{r}. (Skär or Skier) Rock (Norwegian)
St. (Stor) Great, Street (Norwegian)
St^{n}..........Station
Str..........Strait
S.F.B. ...Submarine Fog Bell
Tel. ....Telegraph
Temp^{y}. .... { Temporary
Temporarily.
T^{g}. (Tanjong) Point (Malay)
T^{k}. (Telok) Bay or Cove (Malay)
T^{r}., T^{re}. ...Tower
Uj^{g}. (Ujong) Cape or Point (Malay)
Uncov. ...Uncovers, Uncovered
V^{a}. (Villa) House or Town
Var^{n}. ......Variation
Vel. ....Velocity
Vil. ....Village
Vol. ....Volcano
W. (Wadi) River (Arabic)
Wh^{f}. ....Wharf
W.T. Wireless Telegraph Station.
Y^{a}. (Yama) Mountain (Japanese)
Y^{ds}. ....Yards
Z^{i}. (Zaki) Cape or Point (Japanese)

162. System of buoyage in the United Kingdom.—The positions of rocks and shoals are generally indicated by buoys. The shape and colour of a buoy depend on its position relative to the danger which it marks, and buoys should be used so as to conform to the following rules:—

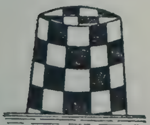
By the term starboard hand is meant that side which will be on the right hand when going with the main stream of flood tide, or when entering a harbour, river, or estuary from seaward.

By the term port hand is meant that side which will be on the left hand under the same circumstances.

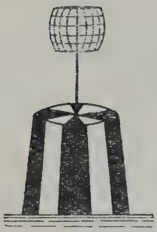

Black.
Fig. 133.

Starboard hand buoys, that is buoys which mark the starboard side of a channel as above defined, show the top of a cone above water and are called conical buoys; they are painted one colour; in England, red or black; in Scotland and Ireland, red only.

In order to distinguish readily particular starboard hand-buoys in a channel, certain of them are surmounted by a topmark, consisting of a staff and one or more globes as shown in Fig. 133.


Red and white chequers.
Fig. 134.

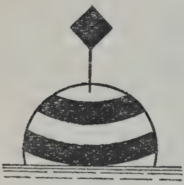
Port hand buoys, that is buoys which mark the port side of a channel as above defined, show a flat top above water and are called can buoys; they are painted as follows:—in England, red and white or black and white, showing chequers or vertical stripes, Figs. 134 and 135; in Scotland and Ireland, black. These buoys are distinguished by a topmark consisting of a staff and cage as shown in Fig. 135.



Black and white vertical stripes.
Fig. 135.

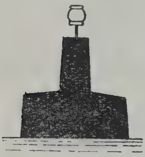
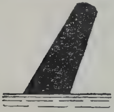
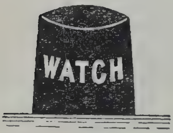
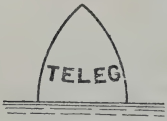
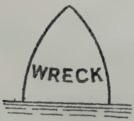
Buoys on the same side of a channel are distinguished from one another by names, numbers, or letters.

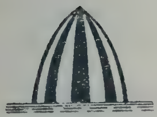
A middle ground, which is a shoal with a channel on either side of it, has its ends marked by buoys which show a domed top above water; these are called spherical buoys and are coloured with horizontal stripes. A spherical buoy surmounted with a staff and diamond (Fig. 136) marks the outer end of a middle ground, and a spherical buoy surmounted by a staff and triangle marks the inner end.



Black and white horizontal stripes.
Fig. 136.

There are various other buoys which are used for special purposes, as shown below:—

Shape and colour.	Name.	Where used.	Remarks.
	Pillar buoy.	Generally to mark a fairway in a channel.	Generally carries a light.
	Spar buoy.	In special positions.	
 Red.	Watch buoy.	In vicinity of lightships.	To indicate to lightship keepers if their vessel is maintaining its position.
 Green.	Telegraph buoy.	Over a telegraph cable.	
 Green.	Wreck buoy.	Near a wreck.	Moored on that side of the wreck which is nearest mid-channel.

 Yellow and Green.	Spoil ground buoy.	To mark limits of a spoil ground.	By a spoil ground is meant an area where dredgers and hoppers discharge. These buoys are not for the purposes of navigation, and may be of any shape.

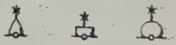
Any buoy may carry a light, an automatic whistle, or a bell.

A wreck may be marked by a wreck marking vessel which is painted green with the word wreck painted in white letters. A wreck marking vessel carries three balls suspended from a yard, two in a vertical line from one yardarm and one from the other, the single ball being on the side next the wreck. By night such a ship carries three fixed white lights similarly arranged but does not carry the ordinary riding light.

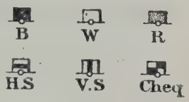
It is manifestly impossible that any reliance can be placed on buoys always maintaining their exact positions. Buoys, especially when in exposed positions, should therefore be regarded as warnings and not as infallible navigating marks, and a ship should always, when possible, be navigated by observations of fixed objects and not by buoys.

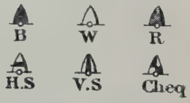
The lights shown by buoys cannot be implicitly relied on, because if they happen to be extinguished a long interval may elapse before they are relit, particularly in bad weather.

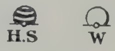
Buoys are depicted on the charts as shown below:—

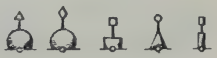
Light Buoys ....


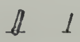
Bell Buoys ....

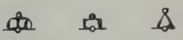
Can Buoys ....


Conical Buoys ....


Spherical Buoys.................................


Buoys with Topmarks ....


Spar Buoys..


Mooring Buoys ....


The little circle shown in the centre of the water line of a buoy as depicted on the chart indicates the actual position of the buoy.

The following abbreviations shown below buoys on a chart indicate the characteristics of the buoys :—

B., Blk	Black
Cheq	Chequered
G.	Green
Gy.	Gray
H.S	Horizontal Stripes
No.	Number
R.	Red
S.B.	Submarine bell (Sounded by wave action).
S.F.B.	Submarine Fog Bell (Mechanically sounded).
V.S	Vertical Stripes
Y.	Yellow
W., Wh.	White

163. System of lighting.—Lighthouses and light vessels are placed, for convenience in navigation, to mark various prominent points of the coast and certain rocks and shoals ; full details respecting them are given in a book entitled "The Admiralty List of Lights and Time Signals."

The light shown may be a continuous steady light, or it may be varied by the introduction of flashes, eclipses, &c. Lights are generally divided into two classes, namely :—

(1) Lights whose colours do not alter throughout the entire system of changes.
(2) Lights which alter in colour.

The abbreviations used in the Admiralty List of Lights, as well as the characteristic phases of the lights, are given in the following table :—

Lights whose colours do not alter.	Characteristic phases.	Lights which alter in colour.
F. Fixed	A continuous steady light	Alt. Alternating.
Fl. Flashing	(*a*) Showing a single flash at regular intervals, the duration of light being always less than that of darkness. (*b*) A steady light with a total eclipse at regular intervals; the duration of light being always less than that of darkness.	Alt.Fl. Alternating flashing.
Gp.Fl. Group flashing.	Showing a group of two or more flashes at regular intervals.	Alt.Gp.Fl. Alternating group flashing.
Occ. Occulting	A steady light with a sudden and total eclipse at regular intervals; the duration of darkness being always less than, or equal to, that of light.	Alt.Occ. Alternating occulting.

Lights whose colours do not alter.	Characteristic phases.	Lights which alter in colour.
Gp.Occ. Group occulting.	A steady light with a group of two or more sudden eclipses at regular intervals.	Alt.Gp.Occ. Alternating group occulting.
F.Fl. Fixed and flashing.	A fixed light varied by a single flash of relatively greater brilliancy at regular intervals. The flash may, or may not, be preceded and followed by an eclipse.	Alt.F.Fl. Alternating fixed and flashing.
F.Gp.Fl. Fixed and group flashing.	A fixed light, varied at regular intervals, by a group of two or more flashes of relatively greater brilliancy. The group may, or may not, be preceded and followed by an eclipse.	Alt.F.Gp.Fl. Alternating fixed and group flashing.
Rev. Revolving.	Light gradually increasing to full brilliancy, then decreasing to eclipse.	Alt.Rev. Alternating revolving.

The letter (U), against the name of a light in the Light List, indicates that the light is unwatched. Caution should be exercised when expecting to sight an unwatched light, because some interval may elapse before it is re-exhibited if it should become extinguished from any cause.

The period of a light is the interval between successive commencements of the same phase.

The order of a light is a conventional term which refers to the focal distance of the apparatus, the focal distance being the distance from the centre of the illuminant to the inner surface of the lens. Lights are divided into six orders; the power of the lights however does not vary directly with the order, and whenever obtainable the candle power is given in units of 1,000 candle power. The small letter in brackets, which follows the name of a light in the Light List, indicates the authority responsible for that light.

All bearings of lights given in the Light List are true and are given from seaward.

In the case of lights which do not show the same characteristics or colours in all directions, the areas over which the different characteristics are shown are indicated on large scale charts by sectors of circles. The arcs of the circles do not denote the distance at which a light may be seen.

All the distances given in the Light List, and on the charts, for the visibility of lights are calculated for a height of an observer's eye of 15 feet. The table at the beginning of each Light List for the distances at which lights should be visible due to height, or the table in Inman's Tables for the distance of the sea horizon, (§ 57), affords a means of ascertaining how much further the light might be visible should the height of the bridge be more than 15 feet. The glare of a powerful light is often seen far beyond the limit of visibility of the actual rays of the light, but this must not be confounded with the true range. Refraction may often cause a light to be seen at a greater distance than under ordinary circumstances (§ 52).

When looking out for a light at night, it should not be forgotten that the range of vision is much increased from aloft. By noting a star immediately over the light, a very correct bearing may be afterwards obtained from the standard compass.

The intrinsic power of a light should always be considered when expecting to make it in thick weather. A weak light is easily obscured by haze and no dependence can be placed on it being seen. The power of a light whose candle power is not given can be estimated by remarking its order, as given in the Light List, and in some cases by noting how much its visibility in clear weather falls short of the range due to the height at which it is placed. Thus a light standing 200 feet above the sea, and only recorded as visible at 10 miles in clear weather, is manifestly of little brilliancy, because its height would permit it to be seen at a distance of over 20 miles provided that its candle power were sufficient.

The distance from a light cannot be estimated by either its brilliancy or its dimness.

On first making a light from the bridge, by at once lowering the eye several feet and noting whether the light dips, it may be determined whether the vessel is in the circle of visibility corresponding to the usual height of the eye, or unexpectedly nearer the light.

The following abbreviations with reference to lights are employed on the Admiralty charts :—

★ ✱ •	Lights, Position of
L^{t}.,L^{ts}	Light, Lights
L^{t}.Alt.	Light Alternating
L^{t}.F.	,, Fixed
L^{t}.Fl.	,, Flashing
L^{t}.Occ.	,, Occulting
L^{t}.Rev.	,, Revolving
L^{t}.F.Fl.	,, Fixed and Flashing
L^{t}.Gp.Fl.(3)	,, Group Flashing
L^{t}.F.Gp.Fl.(4)	,, Fixed and Group Flashing
L^{t}.Gp.Occ.(2)	,, Group Occulting.
Alt.	alternating
ev.	every
fl.fl^{s}.	flash, flashes
G.,G^{n}.	Green
Gp.	Group

hor^{l}	horizontal (Lights placed horizontally)
irreg	irregular
m.	miles
min.	minute or minutes
obsc^{d}.	obscured
occas^{l}.	occasional
R.	Red
sec.	second or seconds
(U)	Unwatched
vert^{l}.	vertical (Lights placed vertically)
vis.	visible
W.,Wh.	White

The number in brackets after the description of Group Flashing or Group Occulting Lights denotes the number of flashes or eclipses in each group.

Alt. (Alternating) signifies a Light which alters in colour.

The height given against a light is the height of the focal plane of the light above High Water of ordinary Spring Tides, or above the sea level in cases where there is no tide.

As an example it will be found that the Eddystone light is marked on large scale charts :—

Lt.Gp.Fl. (2) ev. 30 secs. 133 feet vis. 17m.

This signifies that the light shows a group of two flashes, the period between the commencement of consecutive groups being 30 seconds ; the centre of the lantern is 133 feet above the level of high water of ordinary spring tides ; and at this state of the tide, on a dark night with a clear atmosphere, the light is visible up to a distance of 17 miles to an observer whose height of eye is 15 feet.

Light-vessels in English and Scottish waters are painted red with their names in white letters ; in Irish waters they are painted black. The approximate height of the day-mark (a distinguishing mark carried at the masthead) above the waterline and the description of the light-vessel is given in the Light List.

Light-vessels carry riding lights to indicate the direction in which they are swung.

If a light-vessel is adrift from her moorings, or out of position, by day her day-mark is lowered ; by night her ordinary lights are lowered, a red light is shown at each end of the vessel, and a red flare-up is shown every 15 minutes.

If, from any cause, a light-vessel is unable to exhibit her usual lights whilst at her station, the riding light only is shown.

164. Fog-signals.—There are various kinds of fog-signals :—gun, explosive report, siren, horn, bell, gong, automatic whistle, and submarine bell.

Signals by gun or explosive report are generally employed in light-houses and light-vessels which mark outlying rocks, and sometimes on important headlands.

The siren, sometimes distinguished by high and low notes, is generally employed on headlands and important light-vessels. It has been found that, under certain conditions of the atmosphere, when a fog-signal is a combination of high and low notes one of the notes may be inaudible.

The horn and gong are also used in light-vessels and light-houses.

Bells are sometimes established in light-houses and light-vessels but more frequently on buoys.

Submarine bells are fitted in light-vessels, and at certain positions on the sea bottom where they are electrically operated from a station on shore.

Buoys, when provided with a sound signal, are generally fitted with a bell or automatic whistle. Submarine bells are fitted to some buoys, in which case they are rung by the action of the waves.

Wreck-marking vessels sound a bell and gong alternately during fog.

When listening for a fog-signal, from a buoy or an unwatched light-vessel, it should be remembered that the signal is worked by the motion of the sea ; consequently, in a calm, the signal will probably not be heard.

165. Reliability of fog-signals.—Sound is conveyed through the atmosphere in a very capricious way. Apart from wind or visible obstructions, large areas of silence have been found, in different directions and at different distances from the origin of sound, even in the very clearest of weather and under a cloudless sky. From a long series of observations it has been discovered that sound is liable to be intercepted by streams of air which are unequally heated and unequally saturated with moisture, in fact by a want of homogeneity in the interposed atmosphere. Under such conditions the intercepted vibrations are weakened by repeated reflections, and possibly may fail to reach the ears of persons although well within the ordinary limits of audibility. The observations clearly proved that rain, hail, snow and fog have no power to obstruct sound, and that the condition of the air associated with fog is favourable to the transmission of sound. Therefore while one may expect to hear a fog-signal normally both as to intensity and place, the foregoing should be taken into account and occasional aberration in audition prepared for. It has been found that when approaching a fog-signal with the wind one should go aloft, and when approaching it against the wind the nearer one is to the surface of the water the sooner will the signal be heard.

The apparatus for sounding the signal frequently requires some time before it is in readiness to act.

A fog often creeps imperceptibly towards the land, especially at night, and is not noticed by the lighthouse keeper until it is upon him; whereas an approaching ship may have been for many hours in the midst of it.

166. Submarine bell.—Sound-waves in air travel at the rate of about 1,130 feet per second, but as stated above (§165) the progress of ærial sound-waves is very variable. In water sound-waves travel about four times as fast as in air and their progress is far less variable; when discharged, they spread out in all directions, but are deflected by shoals, land, and breakwaters, and possibly by strong tidal streams and currents.

The present form of submarine sound signal consists of a bell, worked electrically, which is either suspended under the keel of a light-vessel or is slung from a tripod resting on the bottom of the sea in the vicinity of a light-house. Submarine bells are also fitted to buoys, but in this case, when listening for the sound, it should be borne in mind that the bell is only worked by the motion of the sea. Details of submarine bells are given in the remarks column of the Light List.

The various light-vessels, light-houses, &c., give signals which are distinguished from one another by the number and combination of strokes. The receiver is the bottom plating of the vessel. The vibrations are conveyed from the bottom plating of the vessel to the chart house by means of the receiving gear, which consists of microphones secured to the ship's side at about 18 feet below the water line and 66 feet from the bows. The microphones are generally in pairs, marked A and B, and are connected electrically to two telephone receivers in the chart house, a two-way switch enabling the operator to listen on either side of the ship at will. The sound is heard loudest when it is at right angles to the microphone or about 2 points before the beam, and the sound is lost when it is about 4° on the bow or about 6 points abaft the beam, according to the class of the vessel.

It is essential in order to obtain good results that all noise in the compartment in which the microphones are situated should be stopped, and that the ship should be as quiet as possible. For this reason it is found that the best results are obtained when the speed of the ship is low.

To obtain the bearing of a submarine bell listen on either side of the ship alternately till the sound of the bell is heard, then, still listening on the side where the sound was first heard, alter course slowly towards the bell and note the direction of the ship's head when the sound of the bell is lost; immediately put the switch over, listen on the other side and note the direction of the ship's head when the sound of the bell is again heard. The mean of the two directions of the ship's head should be the bearing of the bell. As a check the operation should be repeated whilst turning back to the original course. With a little practice the bearing of the bell can be found with considerable accuracy, the distance at which this can be done varying from about 2 to 15 miles.

167. Printing of the chart.—Charts are printed from engraved copper plates, but, as copper is a comparatively soft metal, constant printing wears down the surface of the plate and the engraving soon becomes shallow and indistinct; to meet this difficulty and prolong the life of the plate a method of electrically depositing steel on its surface has been adopted. Although the deposit is almost an immeasurable quantity, the effect is such that 10,000 copies can be pulled from a steel-surfaced plate with less damage to it than 1,000 copies when the plate is unsteeled.

To print or pull an impression from a copper plate, the printer first cleans the surface thoroughly, then dabs the whole surface over with printing ink until he is satisfied that every cut in the plate is filled. He then rubs the surface of the plate over quickly and lightly with his hands until all the surface ink is removed. The plate is then rubbed over with whitening and polished, after which it is placed on the bed of the printing press and a sheet of paper laid on it; it is then drawn through the press and considerable pressure is applied. When the plate emerges from the press the paper is carefully lifted from it and the necessary proof is obtained.

Charts used in navigation are printed on paper that has been slightly damped in order to take a good impression; this damping causes a slight distortion due to shrinkage when the paper dries, the amount of which can be easily obtained by measuring the proof between the inner border lines and comparing the measurements with those engraved in the bottom right hand corner of the chart. As a general rule the distortion is not sufficient to cause an appreciable error in the position of a ship, and the larger the scale of the chart the smaller is the error; for this reason, as well as for others, that chart of the locality which is on the largest scale should always be used.

In addition to the wear and tear of the plate, printing from copper is a long and expensive method of obtaining chart proofs; it is very much more economical to print from lithographic stones. This is achieved by obtaining a proof from the copper plate in a greasy ink, specially made for the purpose, on a specially prepared paper. Care having been taken that every detail is shown, the proof is laid face downwards on a lithographic stone, which, owing to its nature, takes the impression of the wet greasy ink and thus gives, after certain treatment by the lithographer, another means of obtaining copies of the chart.

Printing from lithographic stones is very inexpensive, for about 2,500 copies can be printed from a stone in an hour, with a steam or electrically driven printing machine; whereas only half a dozen copies can be printed from a copper plate in the same time, and the work has to be almost entirely manual. Owing, however, to the great weight, to the necessary care in handling to prevent breakage, and to the large amount of space required for storing lithographic stones (they are usually from $2\frac{1}{2}$ to 3 inches thick), zinc plates specially prepared with a granulated surface have been found to answer the same purpose, and to possess advantages over the stone as regards handling, breakage, and storage. The processes of transferring to, and printing from, zinc plates are practically the same as when using stones.

Admiralty charts are constructed either on the Mercator's or gnomonic projections, the latter being used when the scale is greater than two inches to the mile and where areas in high latitudes have to be represented.

168. Chart correction.—Charts are kept up to date in the following manner. When information has been received at the Hydrographic Department that a chart requires correction, the information relating to the correction is published in the "Notices to Mariners," which are despatched weekly to all Officers in charge of charts; it is the duty of these Officers to forthwith make the necessary correction with pen and red ink to the charts which are affected.

When making corrections on a chart the instructions issued with the chart set should be carefully followed.

The correction is also placed on the chart plate, the date of such correction being engraved in the left hand lower corner of the margin under the heading "Small corrections."

When a correction is too large to be conveniently placed on a chart by hand, such as when there have been large alterations in soundings or in a coast line, a reproduction of the portion so corrected is sometimes inserted in a Notice to Mariners; this reproduction is printed in two colours, red and black, the correction being in red. When this is not done a new edition of the chart is issued, the date of this new edition being printed on the margin at the bottom of the chart against the words "New editions."

A chart is described by means of its number (in the right hand lower corner), together with the title and dates of publication or new edition, and last small correction; thus, No. 2 British Islands, New edition, 26th June 1912, last small correction, I. 13.

169. Reliability of charts.—The value of a chart manifestly depends on the accuracy of the survey on which it is based, and this becomes more important the larger the scale of the chart. To estimate this, the date of the survey, which is always given in the title, is a good guide. Besides the changes that, in waters where sand or mud prevail, may have taken place since the date of the survey, the earlier surveys were mostly made under circumstances that precluded great accuracy of detail, and until a plan, founded on such a survey, is tested, it should be regarded with caution. It may indeed be said that, except in well frequented harbours and their approaches, no surveys yet made have been so minute in their examinations of the bottom as to make it certain that all dangers have been found.

The fullness or scantiness of the soundings is another method of estimating the completeness of a chart. When the soundings are sparse or unevenly distributed it may be taken for granted that the survey was not made in great detail.

The degree of reliance which may be reasonably placed upon an Admiralty chart, even in surveys of modern date, is mainly dependent on the scale on which the survey was made, and it should not be assumed that the original survey was made on a larger scale than that published.

It should be borne in mind that the only method of ascertaining the inequality of the bottom is by the laborious process of sounding, and that in sounding over any area the boat or vessel which obtains the soundings is kept on given lines; that each time the lead descends only the depth of water over an area equal to the diameter of the lead, which is about two inches, is ascertained, and that consequently, each line of soundings, though miles in length, is only to be considered as representing a width of two inches.

Surveys are not made on uniform scales, but each survey is made on a scale commensurate with its importance. For instance, a general survey of a coast, which vessels only pass in proceeding from one place to another, is not usually made on a scale larger than one inch to the nautical mile; surveys of areas where vessels are likely to anchor are made on a scale of two inches to the mile; and surveys of frequented ports or harbours likely to be used by fleets, are made on a scale of from six inches to ten inches to the nautical mile.

Little assistance in detecting excrescences on the bottom, when sounding from a boat, is afforded by the eye, even in clear weather, on account of the observer being so close to the surface of the water. If, therefore, there is no inequality in the soundings to cause suspicion, a shoal patch between two lines may occasionally escape detection.

Lines of soundings, plotted as close as is practicable on a scale of six inches to the nautical mile, would be 100 feet apart, and each line would be only two inches in actual width. Thus, in a chart on a scale of one inch to the nautical mile, an inequality of some acres in extent rising close to the surface, if it happened to be situated between two lines, might escape the lead; while in a chart on a scale of six inches, inequalities as large as battleships, if lying parallel to and between the lines of soundings, might exist without detection if they rose abruptly from an otherwise even bottom.

General coast charts should not, therefore, be looked upon as infallible, and a rocky shore should on no account be approached within the ten fathom line, without taking every precaution to avoid a possible danger; and even with surveys of harbours on a scale of six inches to the nautical mile, vessels should avoid, if possible, passing over charted inequalities in the ground, for some isolated rocks are so sharp that the lead will not rest on them.

Blank spaces among soundings mean that no soundings have been obtained in these spots. When the surrounding soundings are deep it may reasonably be assumed that in the blanks the water is also deep; but when they are shallow, or it can be seen from the remainder of the chart that reefs or banks are present, such blank spaces should be regarded with suspicion. This is especially the case in coral regions and off rocky coasts, and it should be remembered that in waters where rocks abound it is always possible that a survey, however complete and detailed, may have failed to find every small patch. A wide berth should, therefore, be given to every rocky shore or patch in compliance with the following invariable rule:—*instead of considering a coast to be clear, unless it is shown to be foul, the contrary should be assumed.*

Except in plans of harbours that have been surveyed in detail, the five fathom line on most Admiralty charts is to be considered as a caution or danger line against unnecessarily approaching the shore or banks within that line, on account of the possibility of the existence of undiscovered inequalities of the bottom. The ten fathom line is, on a rocky shore, as beforementioned, another warning, especially for ships of heavy draught.

Charts on which no fathom lines are marked should be especially regarded with caution, for it may generally be concluded that the soundings were too scanty, and the bottom too uneven, to enable them to be drawn with accuracy.

Isolated soundings, shoaler than the surrounding depths, should always be avoided, especially if ringed round, for it is impossible to know how closely the spot may have been examined.

Arrows on charts only show the most usual or the mean direction of a tidal stream or current. It should never be assumed that the direction of the stream will not vary from that indicated by the arrows. In the same manner, the rate of a stream constantly varies with circumstances, and the rate given on the chart is merely the mean of those found during the survey, possibly from very few observations.

170. Sailing Directions.—The Sailing Directions are books which are supplied to H.M. Ships for the purpose of giving detailed information respecting coasts, ports, tides, soundings, &c. Wherever the information given on the charts differs from that given in the Sailing Directions, the information given on the chart of the largest scale, which should have been corrected from the latest information, should be taken as the guide for purposes of navigation.

CHAPTER XVIII.

THE TRACK OF THE SHIP AND THE AVOIDANCE OF DANGER IN PILOTAGE WATERS.

---

171. The track.—Having studied the previous chapter the reader should now be able to read the chart—that is, to picture mentally the surroundings, in particular the relative positions of the various dangers in the vicinity of the ship's track, as well as the various artificial aids to navigation that may be expected to come into view. We have now to explain how the ship's track to a particular destination should be determined, so that the ship may steam in the vicinity of the dangers with the certainty of avoiding them.

The first question to decide when laying off a course on the chart is—at what distance from any danger zone or from the coast is it most prudent for the ship to pass? The governing factors in making a decision are, the nature of the dangers or coast and the depth of water in the vicinity, whether the dangers are marked by light-houses or other artificial aids to navigation, whether the coast is such that the position of the ship can be fixed while passing it, the state of the weather, whether it is day or night, and whether tidal streams or currents are strong in the vicinity.

On short runs along well-surveyed coasts in daylight and clear weather, an offing of about five miles, where the depth of the water is over ten fathoms, is generally sufficient; but where a long distance is to be run along a more or less straight coast, the distance saved by steaming so close to the shore instead of having an offing of, say, ten miles, is of no moment, and a wider berth should be given than where the distance involved is short.

The possibility of an indraught into a deep bay or indentation of the coast must also be borne in mind, for it is found that vessels, when passing such indentations, are frequently set inshore, although the normal direction of the current may be parallel to the general trend of the coast.

Another point that has to be taken into consideration, when in much frequented waters, is the possibility of the ship being constantly compelled to alter course in order to avoid other vessels, and if the majority of the alterations of course are made to the same side, which is often the case, the cumulative effect of these may seriously displace the vessel; consequently, disregard of this point may cause an otherwise carefully estimated position to be considerably in error.

The general rule when coasting, that is when steaming along and in sight of a coast, is to pass sufficiently close to the coast to enable all prominent marks, such as light-houses, &c., to be seen, and to fix the ship's position frequently, for only by so doing can one be certain of immediately discovering whether the ship has been set off her supposed track by an unexpected current, &c.

To decide at what distance from dangers and coasts the ship should pass requires experience, but the course steered should as far as possible be such that, in the event of the marks being obscured by fog or mist, the ship could still be navigated with the certainty that she is not running into danger.

When, of necessity, the track will lead the ship into comparatively shallow water, such as the estuaries of rivers or the approaches to harbours, it is essential to study the height of the tide as well as the draught of the ship. An ample margin of depth should always be allowed, and the importance of this margin is accentuated, if possible, when the navigation is to be performed on a falling tide.

It should be remembered that the draught of a ship is greater when steaming fast than when she is at rest,[*] and that the draught is very considerably increased when a ship rolls or heels heavily. The amount of the increase in a ship's draught due to rolling or heeling depends on the type of ship, being greatest in ships whose cross section below the water line is approximately rectangular, and it is further augmented when bilge keels are fitted at the corners of the rectangle or if there is much "tumble home" in the cross section above the normal water line. In certain classes of ships the increase is as much as 7 inches per degree of heel, so that for 10° the increase would amount to nearly 6 feet.

In order to conduct a vessel in safety when in the vicinity of land or dangers, the principles of the terrestrial position line, explained in §§ 48, 49, and 50, are employed and the ship's track should, as far as possible, be so arranged that it coincides with a terrestrial position line, in order that repeated observations of the terrestrial point from which the position line results may indicate at once any deviation of the ship from her intended track; and, in addition, if the ship is known to be following her intended track, that a position line from a bearing of an object abeam may at once give her position.

172. Leading marks.—When possible it is convenient to so arrange the track that two objects in transit may be seen ahead or astern, in other words that the ship may steam along the position line resulting from this transit (§ 63). Provided the two objects are seen to remain in transit certainty exists that the ship is following the arranged track, whereas, if they are seen to be not exactly in line with one another, it is obvious that the ship is to the right or left of the pre-arranged track.

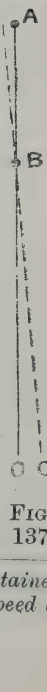


Fig. 137.

Marks are said to be open when they are not exactly in transit, thus in Fig. 137, two lights, *A* and *B* are in transit to an observer at O, but to an observer at C, A is said to be open to the right of B.

---

[*] *An instance is on record of a vessel having grounded and sustained considerable damage in consequence of increased draught due to her speed of 14 knots.*

In many plans of harbours two marks are shown, which, being kept in transit, lead the ship clear of dangers, or in the best channel. Such marks are called leading marks, and their presence is indicated on the chart by a line drawn through them. The line is generally shown on the chart as one straight line, but sometimes as two parallel lines close together. The line is full for a portion of its length and then becomes dotted; this signifies that it is only advisable to keep on it as far as the full line extends, the dotted portion merely being drawn to guide the eye to the objects which are to be kept in transit. The names of the objects and their magnetic and true bearings when in transit are generally written along the line drawn through them. The magnetic bearing is only strictly correct during the year for which the variation on the chart is given.

When the objects are in transit, a bearing of them should be taken and compared with that given on the chart; this ensures that the two objects seen in transit are the correct ones, and is a necessary precaution to take when visiting a place for the first time.

The distance between the leading marks should be roughly noted as a guide to the amount of reliance that can be placed on them, and to the amount of care necessary while watching them. When making use of leading marks, those which are a considerable distance apart, compared with the distance of the ship, are most trustworthy, and such marks are called sensitive, because the slightest deviation from the correct line will immediately open the marks, whereas, if the marks are close together they will still appear in transit when the ship is at some distance from the line. No absolute rule can be laid down as to the distance the marks should be apart; but if it is a third to a quarter of the greatest distance for which they will be required, it will generally be sufficient.

In Fig. 146 two leading marks are shown. (1) *Red stripe on West end of coastguard building in line with beacon*, N. 45° E.; this leads clear of the dangers Harbour-rock and Carrig-a-bo, and as the distance between the marks is about a third of the greatest distance for which they will be required, this transit is fairly sensitive; (2) *Dunboy turret in line with South extreme of Old Fort Point*, N. 86° E.; this leads in the deepest water, and the distance between the marks is half the greatest distance for which they will be required.

When steadying the ship on leading marks ahead, the order "steady" may be given when the ship's head is pointing exactly to the marks, but when the leading marks are astern, the ship must be steadied by compass in the required direction, when a glance astern at the marks will show whether the ship is on the correct line or not.

173. Lines of bearing.—If no transit marks are available the track should be arranged, if possible, so as to coincide with a line of bearing, (§ 48). In this case the track is drawn on the chart so as to pass through some well defined object, and the bearing of the object from any point of the track noted; the object selected should be ahead of the ship rather than astern. Provided that the bearing of the object remains constant at the bearing noted, the ship must be on the line of bearing which coincides with the pre-arranged track; should the bearing of the object be seen to change, it is obvious that the ship has been set off her track in that direction which is indicated by the change of bearing.

When laying off a line of bearing an object should be selected which is not too far off; the closer the object is to the observer, the easier it is to detect by the change of the bearing when the ship is being set off the line; for example, if the object is one mile distant, the bearing will alter one degree if the ship is set about 30 yards off the line, whereas, if it is ten miles distant, the ship will be set about two cables off the line before the bearing changes one degree.

174. Turning on to a predetermined line.—Having decided on the track proposed for the ship, it is necessary to consider how to determine the instant at which the helm should be put over when altering from one course to another, so that the ship, when steadied on her new course, may be exactly on the pre-arranged track. To do this the distance to new course, or the advance and transfer, is made use of (§ 44). Thus, suppose a ship is steaming N.E. and that it is desired to alter course to North so as to steam along the line *YZ* (Fig. 138). From any point *X* on *YZ* lay off *XP′* in the opposite direction (S.W.) to the present course and equal to the distance to new course for the required alteration.

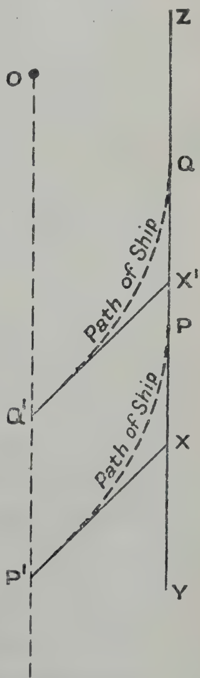


Fig. 138.

Through *P′* draw a line *P′Q′* parallel to *YZ*, then the ship will turn on to the line *YZ* if the helm is put over when she is on the line *P′Q′*, wherever she may be on that line, and she will follow a path such as *P′P* or *Q′Q* till she heads North. Therefore, if the line *P′Q′* is drawn on the chart and it is found to pass through some object *O*, the course should be altered when the ship reaches the position line *OP′*.

Thus we have the rule for finding the position line on which to put the helm over—draw the estimated and new tracks, and from their point of intersection lay back along the estimated track the distance to new course; this gives the point through which to draw the position line parallel to the new track.

It cannot be expected that ships will always turn exactly as anticipated, for their paths are often much affected by wind, sea, depth of water, &c. The necessary allowances for disturbing influences can only be gained by experience and vary in different ships.

The rule stated above will be made clear by the three following examples.

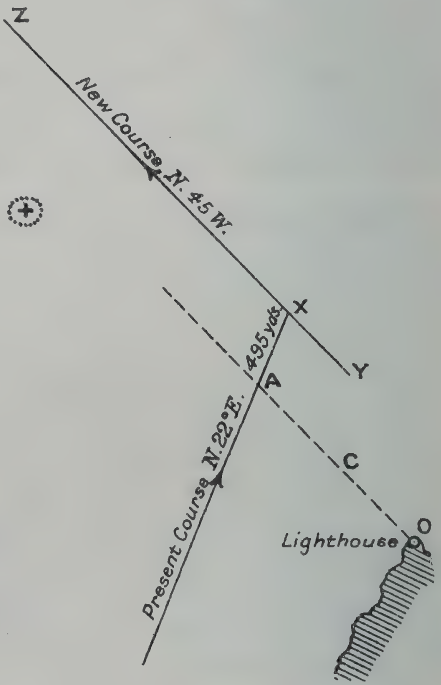


Fig. 139.

Example (1).—A ship is steaming N. 22° E. and it is desired to alter course to N. 45° W. on to the line *YZ* (Fig. 139).

Let the estimated track of the ship intersect *YZ* at *X*.

From the tabular statement relating to the ship's path while turning, the distance to new course for a turn of 67° (from N. 22 E. to N. 45° W.) is found to be 495 yards.

From *X* lay back *XA* along the estimated track equal to 495 yards.

Through *A* draw a dotted line *AC* parallel to *YZ*, then if the helm is put over when the ship is on the line *AC* she will turn as required.

Now it will be observed that *AC*, when produced, passes through the lighthouse *O*, so that the helm should be put over when the ship arrives on the position line resulting from the observed bearing of the light-house being S. 45° E.

It is seldom that an object can be found whose line of bearing exactly coincides with the line AC, but frequently an object can be found whose line of bearing can be drawn parallel to AC and the principle of transferring a position line made use of, as shown in Example (2).

Example (2).—A ship is steering N. 40° W. at 10 knots; the position of the ship is uncertain and it is desired to alter course to North so as to steam along the line YZ which is at a distance of 2 miles from the point O (Fig. 140).

Let the estimated track (N. 40° W.) of the ship intersect YZ in X. From the tabular statement relating to the ship's path while turning, the distance to new course for a turn of 40° (from N. 40° W. to North) is found to be 400 yards.

Lay back, along the estimated track, XA equal to 400 yards. Through A draw a dotted line AC parallel to YZ, then if the helm is put over when the ship is on the line AC, the ship will turn as required.

Through the point O draw a line parallel to YZ intersecting the estimated track at B, then it will be found that AB is 2·9 miles. Note the instant when the point O bears North, that is when the ship is on the position line OB; then, since 2·9 miles is covered at 10 knots in 17·4 minutes, the ship will be on the line AC 17·4 minutes after the point O bore North; at this instant the helm should be put over and the ship will turn on to the line YZ as required.

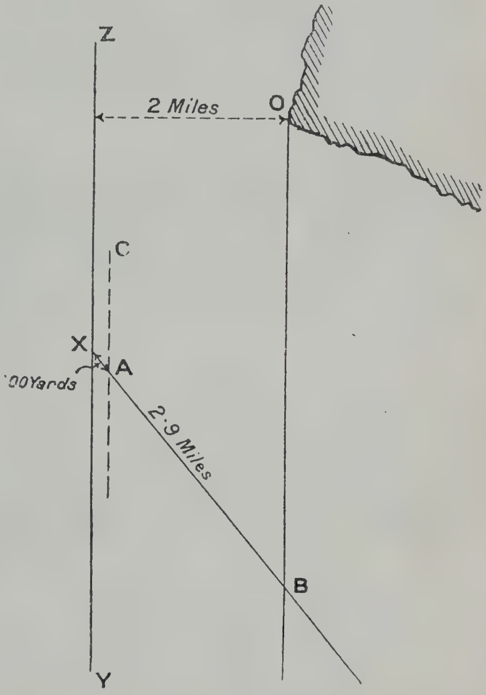


FIG. 140.

When a tidal stream or current is being experienced it should be allowed for as shown in Example (3).

Example (3).—A ship is steaming N. 60° W. at 10 knots; her position is uncertain, and it is desired to alter course so as to make good a course North along the line *YZ* (Fig. 141), which runs through the channel *MO* at a distance of four cables from the point *O*. A tidal stream is estimated to be setting West 1 knot.

To find the course to steer in order to make good a course North, take any point *X* in the line *YZ* and lay off *XG* to represent one knot West on any convenient scale; with centre *G* and radius 10 knots on the same scale describe a circle cutting *XZ* in *H*, then the direction of *GH*, which is N. 6° E., is the course required.

From the tabular statement relating to the ship's path while turning, the distance to new course for a turn of 66° (from N. 60° W. to N. 6° E.) is found to be 495 yards, and the time of turning is found to be two minutes. From *X* lay off *XK* 495 yards S. 60° E.

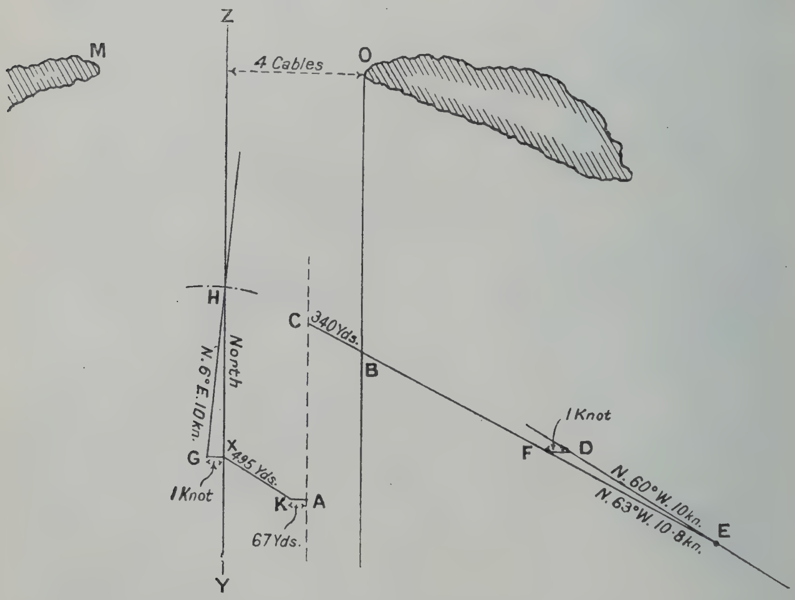


Fig. 141.

While the ship is turning, the tidal stream sets her to the westward a distance of $\frac{2{,}000 \times 2}{60}$ yards or 67 yards. To allow for this set, from *K* lay off *KA* 67 yards East. Through *A* draw a dotted line *AC* parallel to *YZ*, then, if the helm is put over when the ship is on the line *AC*, and the course altered to N. 6° E., she will turn so as to arrive on the line *YZ*.

Through the point *O* draw *OB* parallel to *YZ*. It is now necessary to find what interval should elapse after passing *OB* before the helm is put over; to do this, the course and speed which the ship is making good must be found.

On the estimated track of the ship take any point *E*, and draw *ED* to represent 10 knots N. 60° W. on any convenient scale; through *D* draw *DF* to represent one knot West on the same scale, then *EF* represents the course and speed made good, namely, N. 63° W., 10·8 knots.

Let *EF* produced intersect *OB* and *AC* in *B* and *C* respectively, then the interval required is the time which the ship takes to cover the distance *BC* (340 yards) at 10·8 knots, namely, 57 seconds.

The opportunity for the application of these problems frequently arises in pilotage, and the use of a stop watch is recommended.

Tables, which give the times in which various distances are covered at various speeds, are supplied to H.M. Ships.

When rounding a point which is very close to the ship, and it is desired to keep at a constant distance from it during the turn, the following method may be employed :—Put the helm over, an amount corresponding to the tactical diameter required, a little before the point is on the beam, and subsequently continue to adjust the helm angle so that the object remains abeam throughout the turn.

175. Clearing marks.—Clearing marks are two marks shown on the chart, a straight line through which runs clear of certain dangers ; such a line is shown on the chart with the names of the marks and their magnetic and true bearings when in transit.

When navigating near a danger, care should be taken not to get inside the line of transit of the clearing marks. As long as the ship is kept outside this line, that is, so long as the marks are kept open, she will be safe as far as that danger is concerned.

Figure 142 shows the clearing marks for the Pearl rock at the entrance to Gibraltar Bay, and it will be seen that, when leaving Gibraltar and bound to the Westward, S. Garcia point must be kept open to the Eastward of Carnero point until Black Hill is seen to be in transit with Acebuche point bearing N. 74° W. (272°).

176. Clearing bearings.—When no clearing marks are available we have recourse to a line of bearing, which may be drawn on the chart through some conspicuous point so as to pass at a certain distance from a danger ; such a line is called a clearing bearing and its direction should be noted. By watching the bearing of the object selected, when in the vicinity of the danger, it can immediately be seen if the ship is on the safe side of the clearing bearing.

177. Vertical danger angle.—A useful method of ensuring the safety of the ship when in the vicinity of dangers is the employment of the vertical sextant angle (§ 59).

If the danger to be guarded against is close to high land or a light-house, we proceed as shown in the following example :—It is required to pass at least 4 cables outside a rock which is distant 3 cables from a light-house L, 150 ft. high (Fig. 143).

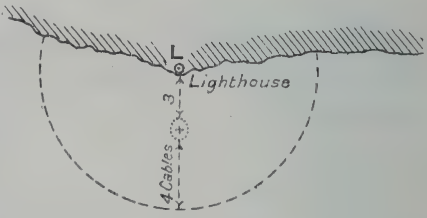


Fig. 143.

With centre L and radius (3 + 4) 7 cables describe a circle. Reference to the *Danger Angle and Off-Shore Distance Tables*, by Lecky, or the formula $\tan \alpha = \frac{H}{D}$ (§ 59), shows that the angle corresponding to this radius is 2° 01′, so that as long as the ship remains outside the circle, the vertical angle subtended by the light-house is less than 2° 01′ ; this angle is called a vertical danger angle.

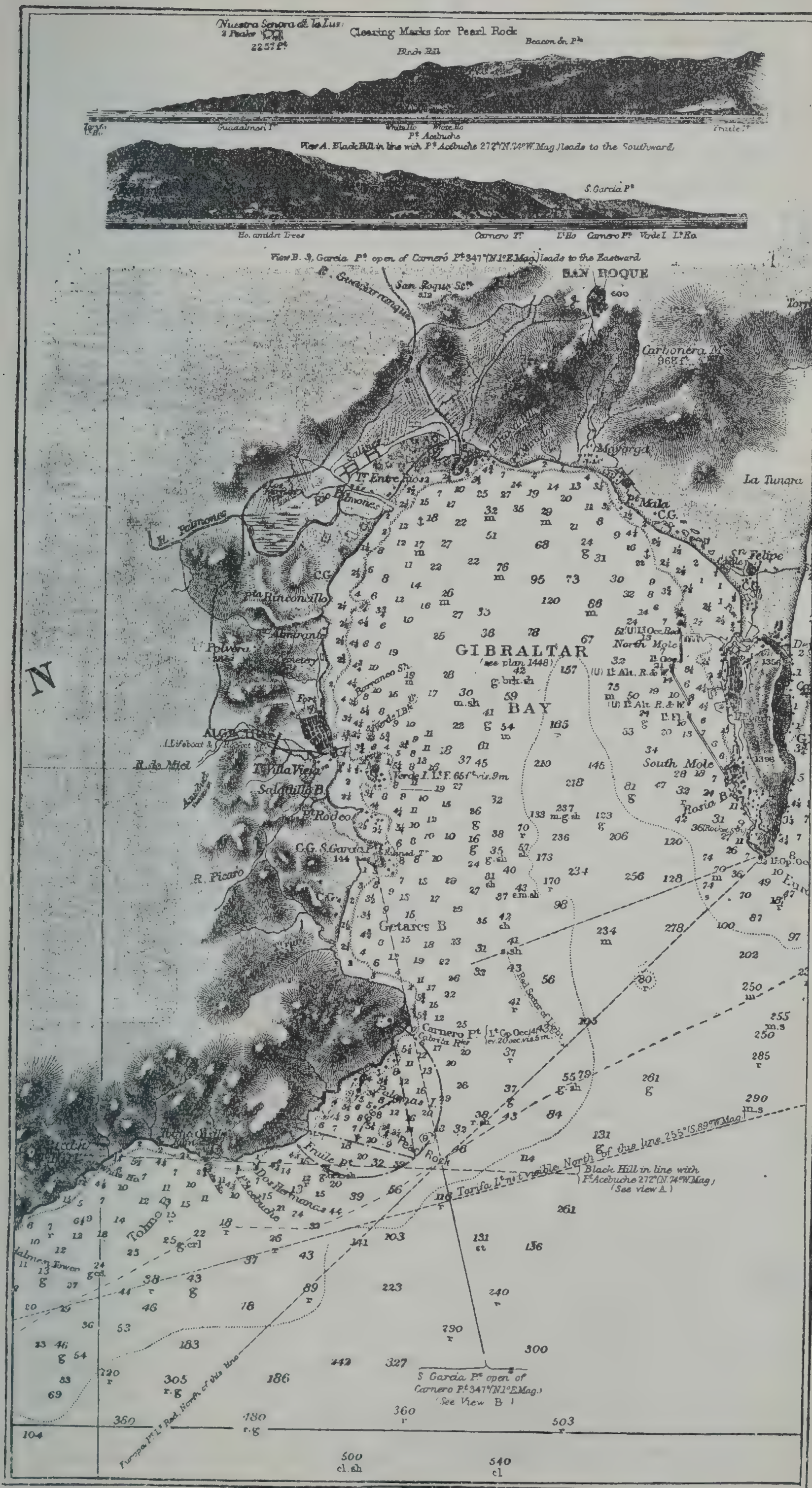

Clearing Marks for Pearl Rock
Nuestra Senora de la Luz
3 Peaks
2237 Ft.
Black Hill
Beacon on Pt.
Guadalmon T.
White Ho
White Ho
Pt. Acebuche
Fraile T.
View A. Black Hill in line with Pt. Acebuche 272° (N. 24° W. Mag.) leads to the Southward
S. Garcia Pt.
Ho. amidst Trees
Carnero T.
Lt. Ho
Carnero Pt.
Verde I.
Lt. Ho
View B. S. Garcia Pt. open of Carneró Pt. 347° (N. 1° E. Mag.) leads to the Eastward
SAN ROQUE
San Roque St.
R. Guadarranque
Carbonera M.
968 ft.
Mayorga
La Tunara
Pt. Mala
C.G.
St. Felipe
T. Entre Rios
R. Palmones
Pta. Rinconcillo
C.G.
Almirante
Pt. Polvera
ALGECIRAS
Lifeboat & Rocket St.
R. de Miel
T. Villa Vieja
Saladilla B.
Pt. Rodeo
Verde I. Lt. F. 65 ft. vis. 9 m.
C.G. S. Garcia Pt.
R. Picaro
Getares B.
GIBRALTAR
(see plan 1448)
BAY
North Mole
South Mole
Rosia B.
Carnero Pt.
Lt. Gp. Occ. (4)
Palomas
Fraile Pt.
Pearl Rock
Dos Hermanos
Pt. Acebuche
Tolmo Pt.
Black Hill in line with Pt. Acebuche 272° (N. 24° W. Mag.)
(See view A.)
Tarifa Lt. not visible North of this line 255° (S. 89° W. Mag.)
S. Garcia Pt. open of Carnero Pt. 347° (N. 1° E. Mag.)
(See View B.)
Europa Pt. Lt. Red North of this line
N

FIG. 142.

The danger angle should be put on the sextant, and so long as the reflected image of the summit appears below the waterline of the light-house, the ship is outside the circle and in safety. Should the ship be closer to the danger than expected and found to be on the circle, she should immediately turn so as to bring the light-house on the beam. When using this method consideration must be paid to the height of the tide as explained in § 60.

178. The horizontal danger angle.—In a similar way the horizontal angle between two fixed objects on shore can be utilized, and the objects should be selected so as to lie at approximately the same distance on either side of the danger to be cleared. A mark should be made on the chart at a distance from the danger equal to that at which it is considered safe to pass, and lines should be drawn from the objects to this mark. The angle thus formed should be measured and the position line corresponding to this angle drawn on the chart, and if the angle between the objects is less than that measured, the ship is outside the danger and in safety. When the angle between the two objects is less than the angle set on the sextant, the image of the reflected object will appear to the left of the object viewed directly through the horizon glass. In Fig. 142, the position line corresponding to a horizontal sextant angle of 66°, between the towers situated on Frayle Point and Carnero Point, is shown; provided the horizontal sextant angle between these two towers is less than 66°, the ship is outside the position line and in safety as regards the Pearl Rock.

179. Avoidance of danger in thick weather.—When the ship is in the vicinity of land or dangers in thick weather the utmost caution should be observed; the speed should be slow and soundings should be continually taken at brief intervals. As already stated (§ 171) the general rule, when coasting, is to sight all marks when passing them, and when the weather is not too thick and the coast is clear of off-lying dangers this rule should be followed; for only by this means can the ship's position be checked from time to time, and thus the possibility of the ship being set towards dangers by unexpected currents or tidal streams be guarded against. When uncertain of the ship's position in thick weather and in the neighbourhood of dangers, the ship should be anchored till the weather clears. There is little risk in so doing if the fall of the tide is taken into consideration, however exposed the position may be, because it is certain that the fog will lift before a strong wind can get up. In the event of it not being possible to anchor, the course should be altered to lead the ship away from the dangers. When close to high land or cliffs the distance off shore may sometimes be found (if the echo of the siren can be heard) by timing the interval between the blowing of the siren and the receipt of the echo. Remembering that sound travels at about 1,130 feet per second, we have the rule that the number of seconds in the interval, diminished by one tenth, is approximately the number of cables in the distance of the ship from the cliff.

Example.—The sound of the echo is heard 10 seconds after the siren was blown.

Required the approximate distance of the cliffs.

$$\frac{1130 \times 10}{2 \times 6080} = \cdot 93 \text{ mile or } 9 \cdot 3 \text{ cables,}$$

or by the approximate method

$$10 - 1 = 9 \text{ cables.}$$

In thick weather look-outs should always be placed high up and low down (§ 165).

The sound of breakers is often heard before the coast can be seen, and the white line of breakers can frequently be seen at a considerable distance in a fog when the land is invisible.

In all circumstances in thick weather, when it is impossible to fix the position of the ship, the lead is the only safe guide. When rounding a point of land in thick weather the soundings on the chart should be carefully examined, and if they are seen to decrease more or less regularly towards the point, a depth may be selected the fathom line of which everywhere passes at a safe distance from the point; care should be taken that the ship does not get into a less depth of water than that selected, due allowance for the height of the tide being made when taking the soundings.

In thick weather special endeavours should be made to keep the reckoning as accurately as possible, and every sounding taken and quality of bottom obtained should carefully be compared with that charted at the estimated position (§§ 67 and 159).

180. Preparing the chart.—When a ship is in pilotage waters the prime desideratum is that all information should be instantly available for use; for this reason, some time before the pilotage waters are entered, the charts, sailing directions, &c., should have been studied and the charts prepared, that is the proposed track as well as all clearing marks, lines of bearing, danger angles, &c., available for assistance in the safe pilotage of the ship, should have been laid off and noted. As stated in § 162 buoys must not be looked upon as infallible navigating marks, and although their positions in pilotage waters should be taken into consideration, it is preferable, when possible, to so arrange the track of the ship that the pilotage entirely depends on fixed objects, and is independent of the buoys.

When leading marks are shown on the chart the track should be arranged so as to make use of them, but when there are no leading marks the pilotage should, as far as possible, depend on lines of bearing.

When selecting an object, on a line of bearing of which it is proposed to steer, consideration should be given as to whether it will be visible from the ship or not; and this can generally be ascertained by examining the height of the object, compared with the height of the intervening land as indicated by the contour lines, and any information that may be given on this point in the sailing directions. Consideration should also be given to the distance of the object selected, because the further the object is from the ship the greater is the displacement of the ship, due to an unknown error in the deviation of the compass (§ 62).

When deciding on the track, Article 25 of the Regulations for preventing collisions at sea should be remembered, namely :—" In narrow channels every steam vessel shall, when " it is safe and practicable, keep to that side of the fairway " or mid-channel which lies on the starboard side of such vessel."

It should also be remembered that, on account of passing vessels, a ship may be compelled to leave the pre-arranged track, and consequently it may happen that a ship is forced to pass closer to a particular danger than was originally intended ; for this reason, clearing marks or danger angles for all dangers, even for those at a considerable distance from the ship's track, and particularly for those situated on the starboard hand, should be included in the preparation of the chart.

The position lines on which the helm should be put over should be drawn, and marks selected as explained in § 174.

All courses, bearings, &c., should be entered in a note book, so as to avoid the necessity of constantly leaving the compass in order to refer to the chart.

When piloting in waters like the entrance to the Thames, where the shore is distant and low lying and it is difficult and sometimes impossible to see any objects on shore, the buoys may be the only guide. Before arriving at such a locality, particularly if the weather is likely to be thick, when preparing the chart, the distances to be steamed on each course and the interval of time required to steam between consecutive buoys should be noted, in order that, in the event of a fog coming on, the time may be known beforehand when each particular buoy should be abeam, due allowance having been made for the effect of tidal streams. Should a buoy not be sighted and passed at the calculated time, it should be assumed that the ship is not passing along the pre-arranged track at the intended speed, and the utmost caution should be observed. The ship should be anchored if there is any uncertainty about her position, the depth of water at low tide having been first considered.

181. Selection of a position in which to anchor.—When selecting a position in which to anchor the ship numerous points have to be taken into consideration, namely, the depth of water and nature of the bottom, whether the bottom is good or bad holding ground (§ 159), whether the anchorage is in a landlocked harbour or in an open roadstead, the direction and probable strength of the prevailing wind, the strength and direction of the tidal streams, and the rise and fall of the tide. The length and draught of the ship, and whether she is to be at single anchor or moored, as well as the position of the landing place, have also to be taken into account.

It is impossible to give any definite rule as to how near a danger a ship may be anchored, but in all cases an ample margin of safety should be allowed in order to meet the contingency of bad weather coming on and the ship dragging her anchors. If the ship is to be moored, the direction of the line joining her anchors should coincide, when possible, with that of the prevailing wind or tidal stream, and each anchor should be sufficiently far from dangers to enable it to be weighed without inconvenience whatever the direction of the wind may be. If no accurate chart of the anchorage is at hand, soundings should be carefully taken within a radius of at least three cables from the ship, in order to ascertain if there are any uncharted rocks or dangers.

182. To anchor a ship in a selected position.—Having selected the position in which to anchor the ship the chart should be prepared as follows:—Select some conspicuous object on shore, the line of bearing of which from the selected position gives a possible line on which the ship may approach, and, if possible, select a second object on the same bearing in order that the ship may approach the selected position with the two objects in transit. The remaining part of the chart should then be prepared as explained in § 180, the track being so arranged that the final course will be along this line, and that the ship will be turned on to it as far from the selected position as possible. Thus, in Fig. 144 let *A* be the position selected for the anchor, then the line which passes through Flagstaff and Church Spire (N. 22½° E.) gives a possible line of approach, because it passes through *A* and runs clear of all dangers; the track of the ship should then be so arranged that her final course will be along this line.

From *A* lay back *AX* along the line of approach equal to the distance between the anchor bed and the standard compass, or between the stem and standard compass when the ship is fitted with stockless anchors; then *X* is the position of the standard compass at the instant the anchor should be let go.

In order to determine the instant at which the standard compass will be at *X*, a position line should be laid off through the point *X* such that the angle which it makes with the line of approach is as near a right angle as possible; this position line is generally a line of bearing of an object, the object being on or nearly on the beam, but it may be a circle obtained from a horizontal sextant angle between two objects situated on either bow. Whichever position line may be selected it is important that the bearing or horizontal sextant angle should be altering rapidly, and for this reason a near object should be selected in preference to a distant one, even if the latter is more nearly on the beam; for the same reason the horizontal sextant angle should not be small and the objects not too far away. The sextant being a more exact instrument for measuring angles than the compass, the position line by horizontal sextant angle should be preferred to the line of bearing, provided that the chart is based on an accurate survey.

When about to anchor it is most important to so reduce the speed of the ship that, when the anchor has been let go and the engines reversed, the ship may be stopped without any strain being brought on the cables; for this reason, when coming to with single anchor, it is customary to reduce the speed of the ship when at about a distance of one mile from the position selected for the anchor, and to stop the engines at a distance of from two to four cables, according to the class of the ship, before arriving at the position for anchoring, and to reverse the engines at the instant of letting go the anchor.

To find where to reduce speed and where to stop the engines, lay back from the point *X* along the line of approach a distance *XZ* of one mile and a distance *XY* of from two to four cables according to the class of the ship; the speed should be reduced (generally to six or seven knots over the ground) when the ship arrives at *Z*, and the engines should be stopped on arrival at *Y*. The instants of arriving at *Z* and *Y* are found in a similar manner to that of arriving at *X*, as will be understood from the following example.

In Fig. 144 the point *A* at which to anchor a ship has been selected, and it is noticed that the line which passes through the Flagstaff and the Church Spire also passes through the point *A* and runs clear of all dangers; it is therefore decided to approach *A* along this line (N. 22½° E.), with the Church Spire and Flagstaff in transit ahead.

From *A* lay back *AX*, 50 yards (the distance between the anchor bed and standard compass), then the anchor should be let go when the standard compass arrives at *X*. Lay the edge of the parallel rulers on the point *X* and in a direction at right angles to the line of approach, and note any conspicuous objects on shore that may be on or near the edge of the rulers; it will be noticed that a monument lies very near the edge of the rulers, its bearing from *X* being S. 72° E.

From *X* lay back *XY*, 2½ cables, and *XZ*, 10 cables, and it will be found that the most suitable object at *Y* is a white house bearing S. 60° E., and at *Z* a beacon bearing N. 50° W.

Therefore the ship, assuming that she has been turned on to the line of approach ZA, should be kept on this line by continually observing that the Church Spire remains in transit with the Flagstaff, care having been taken when first turning on to the line that the bearing of the Church Spire (and Flagstaff) was N. 22½° E. (Mag.). When the beacon bears N. 50° W. the ship's speed should be reduced to, say, 7 knots. When

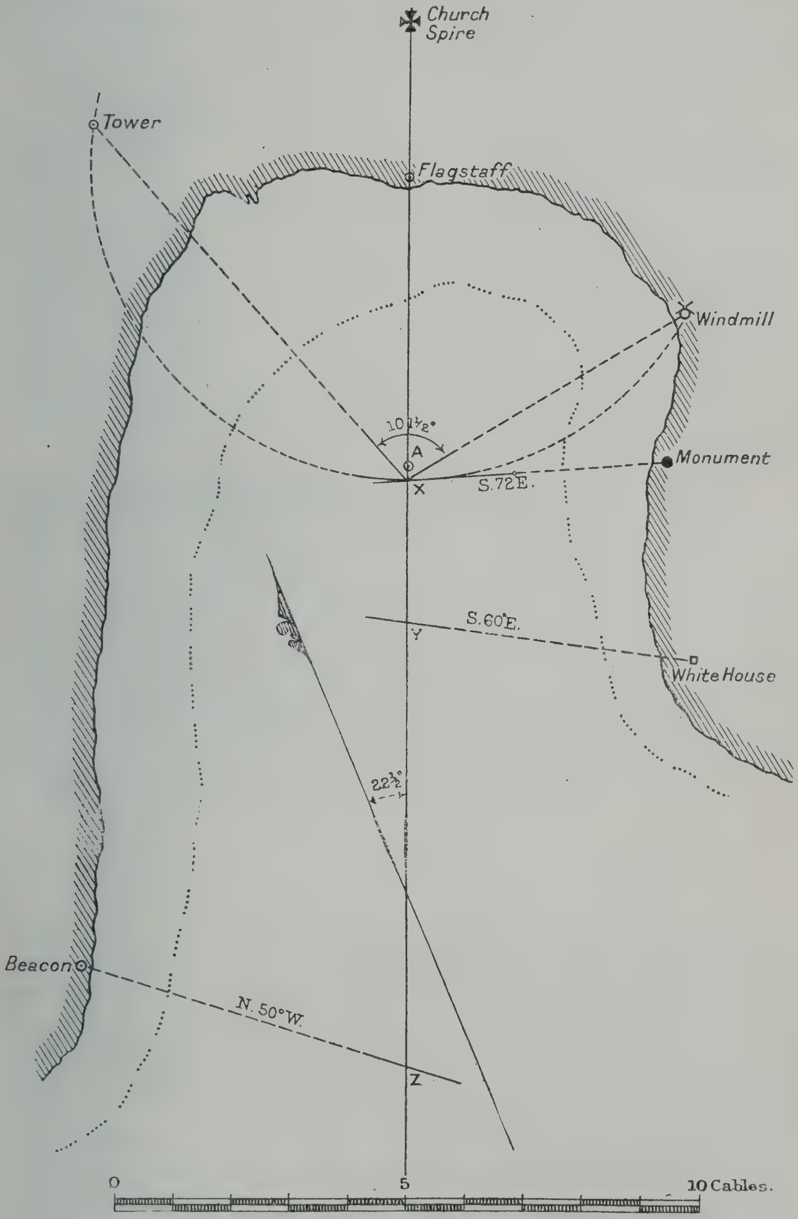


FIG. 144.

the white house bears S. 60° E. the engines should be stopped, and when the monument bears S. 73° E. the anchor should be let go and the engines reversed.

Should there be a tidal stream or current, such a course should be steered that the course made good is along the line *ZA* (§ 25); the distance *XY* will obviously be greater or less according as the tidal stream is with the ship or against her.

It is always advisable to have an alternative position line on which to let go the anchor, in case the object or objects selected should be obscured by trees, or ships already at anchor. When there is not a second suitable object whose bearing is roughly at right angles to the line of approach, a position line by horizontal angle should be employed; for example, in Fig. 144 a segment of a circle passing through the Tower, the point *X* and the Windmill cuts the line of approach nearly at right angles and contains an angle of $101\frac{1}{2}°$, so that if this angle is set on the sextant, the instant of arrival at *X* will be the instant when the images of the Tower and the Windmill are seen in contact through the sextant telescope.

183. To moor a ship in a selected position.—When mooring a ship the same principles are made use of as when anchoring, but in this case it is first necessary to decide what length of cable shall be out on each anchor when the ship has been moored. As a general rule the amount of cable for a heavy ship is six shackles on each anchor. As explained in the Seamanship Manual, one shackle of cable is usually required to go round the bows in order that the mooring swivel may be shackled on, and therefore the distance between the two anchors, when let go, is $(6 \times 2 - 1)$ 11 shackles; therefore the distance of each anchor from the point *A* should be $\frac{11}{2}$ shackles, that is $\frac{11 \times 25}{2}$ or 137 yards. The distance of each anchor from the point *A* should be slightly less where the rise of the tide is considerable or the depth of water great. From *A*, Fig. 145, lay off *AB* and *AC* in both directions along the line of approach, each equal to 137 yards, then *B* and *C* are the positions for the two anchors. From *B* and *C* lay back *BX* and *CX′* each equal to 50 yards (the distance between the anchor bed and standard compass), then the first anchor should be let go when the standard compass arrives at *X*, and the second when it arrives at *X′*. To find when the standard compass arrives at *X* and *X′* we ascertain the bearings of the Monument from these points as when anchoring. The first anchor should be let go when the Monument bears S. $81\frac{1}{2}°$ E. or when the angle between the Tower and Windmill is $92\frac{1}{2}°$; the second anchor should be let go when the Monument bears S. $62\frac{1}{2}°$ E. or when the angle between the Tower and Windmill is 112°.

The positions at which the speed should be reduced and the engines stopped are determined as in the previous example, the distance XY in this case being taken as $1\frac{1}{2}$ cables, because rather more way is required when mooring than when coming to single anchor.

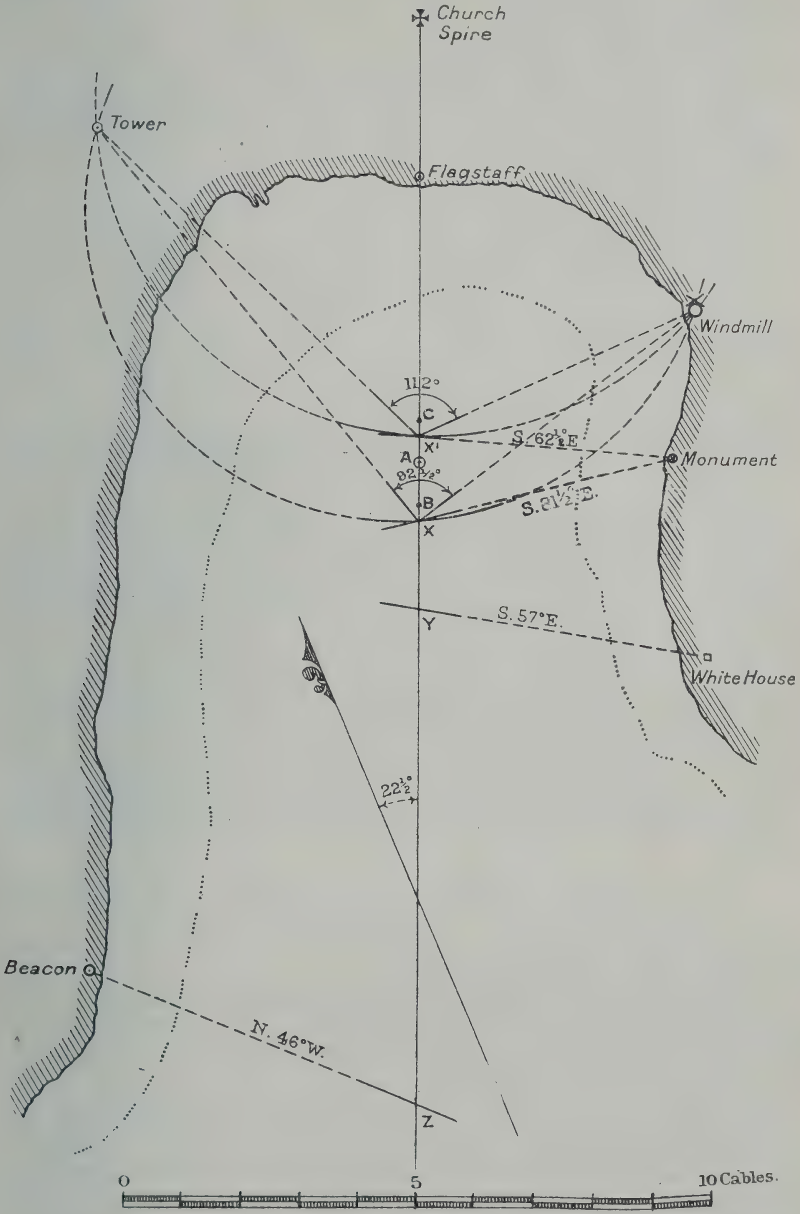


Fig. 145.

The weather anchor should always be let go first in order that the cable may be clear of the stem while the ship is being middled, and great care should be taken that the ship's head is kept perfectly steady till the second anchor has been let go, in order that the cable may be laid out in the straight line which contains the point *A*.

184. Example of the preparation of a chart with a view to anchoring.—The following example shows the method of preparing the chart for entering Berehaven by the Western entrance and taking up an anchorage off Mill Cove. In practice the large scale chart should be used, but for convenient representation in this book the example is shown on a portion of Admiralty chart, 1840. (Fig. 146.)

The necessary details of the ship are as follows:—

Extreme length - - -	400 feet.
Maximum draught - - -	26 feet.
Anchor bed to standard compass -	150 feet.

Alteration of course (in points) - -	2	4	6	8	10
Distance to new course for 15° of helm (in yards) - - - - - - - -	230	365	495	660	885

After consideration it has been decided that in this case a distance of $2\frac{1}{8}$ cables from the five-fathom line gives a sufficient margin of safety, and therefore the point *A*, whose minimum distance from the five-fathom line is $2\frac{1}{8}$ cables, has been selected for the position of the anchor.

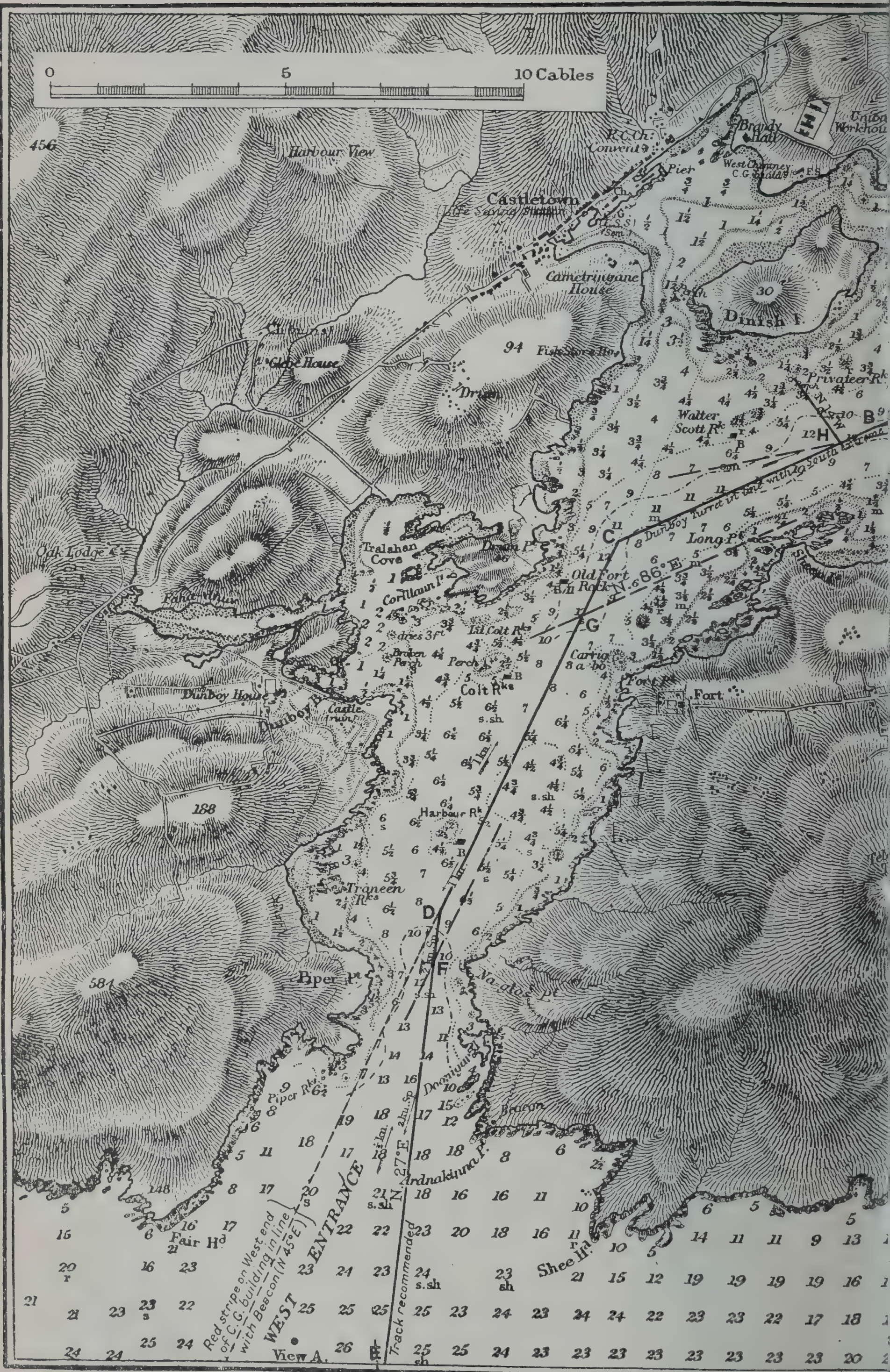
Having the approach in view, lay the rulers on the five-fathom line between the Volage and Hornet rocks and also North-East of Sheep Island, and it will be seen that a line in the direction S. 82° E., when drawn through the point *A*, is a safe course on which to approach *A* and, when produced, passes through the extremity of Carriglea Point (not shown in the Figure).

Through *A* draw a line $\frac{\text{N}}{\text{S}}\ 82^\circ\ \frac{\text{W}}{\text{E}}$, and from *A* lay back *AX* equal to 50 yards; from *X* lay back *XY* and *XZ* equal to $2\frac{1}{2}$ cables and 1 mile respectively.

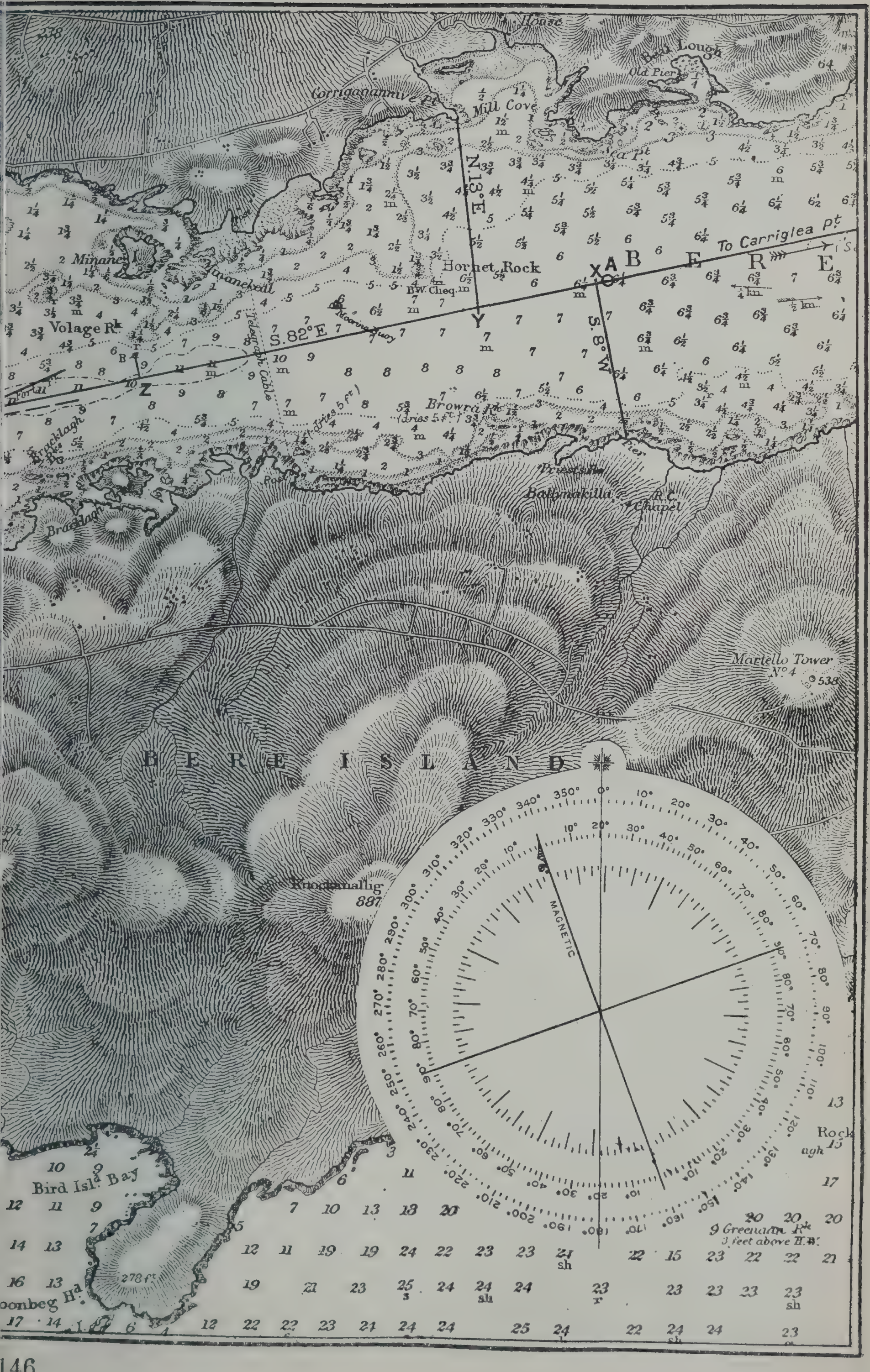
As explained above (§ 182) the pier head on a bearing S. 8° W. gives the position of *X*; Corrigagannive Point on a bearing N. 13° E. gives the position of *Y*; and the Volage Rock buoy abeam gives the position of *Z*.

On examining the chart it is found that two leading marks are given and a track recommended for the Western entrance, and it is noticed that one of the leading marks leads in a depth of $4\frac{3}{4}$ fathoms just North Eastward of Harbour Rock but this will not matter provided the state of the tide is not near low water of ordinary springs. It is therefore proposed to pass through the Western entrance making use of the leading marks.

Let the line *AZ* intersect the leading mark "Dunboy Turret in line with South extreme of Old Fort Point" in *B*, and let


0
5
10 Cables
456
Harbour View
R.C. Ch.
Convent
Brandy Hall
Union Workhouse
Pier
West Chimney
C.G. Station
Castletown
(Life Saving Station)
Cametringane House
Dinish I.
30
94
Fish Store Ho.
Drum
Glebe House
Walter Scott Rk.
Privateer Rk.
B
H
C
Long P.
Dunboy Turret in line with Lo South ...
N. 86° E.
Old Fort Rock
G
Oak Lodge
Tralahan Cove
Dunboy Pt.
Corlllaun Pt.
dries 3 ft.
Bruten Perch
Perch
Ltl. Colt Rk.
Colt Rks.
Carrig a-bo
Fort Pt.
Fort
Dunboy House
Dunboy B.
Castle (ruins)
188
Harbour Rk.
Traneen Rks.
D
F
584
Piper Pt.
Na-glos Pt.
Doonigan
Piper Rk.
Beacon
Ardnakinna P.
Fair Hd.
Shee Hd.
Red stripe on West end of C.G. building in line with Beacon (N 45° E)
WEST ENTRANCE
N. 27° E
Track recommended
View A.
E

Fig


Corriganannive Pt
Mill Cove
Bedi Lough
Old Pier
Sea Pt
N.13°E
To Carriglea Pt
Minane I.
Minanebedl
Volage Rk
Hornet Rock
B.W. Cheq.
X A B E R E
Y
S.82°E
S.8°W
Z
Telegraph Cable
Browra Rk
(dries 5 ft.)
Bracklagh Pt
Bracklagh
Priests Rk
Ballymakilla
R.C. Chapel
Pier
Martello Tower No 4
538
B E R E   I S L A N D
Knockanallig
887
MAGNETIC
Bird Isld Bay
278 ft
oonbeg Hd
Rock
9 Greenane Rk 3 feet above H.W.
¼ kn.
½ kn.

146.

this leading mark intersect the leading mark "Red stripe on West End of Coast-guard building in line with Beacon" in *C*, and let the last mentioned leading mark intersect the recommended track in *D*.

The ship should therefore be steered so as to pass along the track *EDCBX*, due allowances being made for the effects of the tidal stream. In this example it is considered to be slack water, and it is now necessary to find the positions at which the helm should be put over. The course along *ED* is N. 27° E., and along *DC* is N. 45° E. so that the alteration of course is 18°, and from the table above it will be seen that the corresponding distance to new course is 210 yards. From *D* along *DE* lay back *DF* 210 yards, and through *F* draw a dotted line parallel to *DC*; if, therefore, the helm is put over when the ship is on the dotted line through *F* she will turn on to the line *DC*. It will be noticed that the dotted line through *F* passes through the highest point of Dinish Island, so that if the helm is put over when the summit of Dinish Island bears N. 45° E. or when Na-glos Point is just before the starboard beam, the ship will turn on to the leading mark "Red stripe on West end of C.G. building in line with the beacon on Dinish Island" bearing N. 45° E.; it is obvious that the marks must be carefully kept on till Harbour Rock has been passed.

In a similar manner lay back *CG* along *CD* equal to 359 yards, the distance to new course for the next alteration, and note that the dotted line through *G* in the direction of the next course N. 86° E. passes through the Northern extremity of Sheep Island, so that if the helm is put over when this point bears N. 86° E. the ship will turn on to the line *CB*, and Dunboy Turret will be in line with the South Extreme of Old Fort Point, astern. As the ship will in this case be turning on to a stern mark, she must be steadied on N. 86° E. by compass (§ 172). In a similar manner lay back *BH* equal to 160 yards, and draw a dotted line through *H* in the direction of the new and final course S. 82° E. It will be noted that this dotted line does not pass through or near any conspicuous object of which a bearing can be taken, but, if the ship is exactly on the leading marks, the helm should be put over when Privateer Rock Perch bears N. 14° W. If the ship is not exactly on the leading mark, her position should be fixed and the helm put over when she arrives at the dotted line through *H*; the ship should now be steadied on to her final course S. 82° E. which coincides with the bearing of Carriglea Point.

The speed of the ship should be reduced, the engines stopped, and the anchor let go as previously arranged.

It will be noticed that the ship should pass 100 yards off Volage Rock buoy, and this should prove a valuable check on the position of the ship, especially as Carriglea Point (not shown in the Figure) is rather distant for a line of bearing.

185. Conning the ship.—In the majority of ships the officer, whose duty it is to direct the helmsman how the ship is to be steered (to con the ship), is situated in a position from which a comprehensive view of the surroundings can be obtained, but from which he is often unable to see the helmsman; consequently, it is most important that the necessary orders should be given to the helmsman in such a way that no ambiguity can arise.

On arriving at the place where the helm is to be put over the order to the helmsman should be given thus:—"Port 25," "Hard-a-Starboard," &c., particular care being taken to state the amount of helm required.

At some time before the ship's head is in the required direction, depending on the rate at which the ship swings, orders should be given to reduce the helm and to put it amidships, thus "Ease to 20," "Ease to 10," "Midships."

In order that the swing of the ship may just be stopped when the ship arrives on her new course, an order for the requisite amount of opposite helm should be given; or, the helmsman should be given the order "Meet her," when he will check the swing of the ship as rapidly as possible.

When the ship's head comes exactly on to the new course the order "Steady" should be given, and this order means:—keep the ship's head in the direction in which it is at the instant the order "Steady" is received. After receiving the order "Steady" the helmsman should continue to keep the ship's head in the same direction until a further order has been received.

When the helmsman receives the order "Steady" he should report the course, as indicated by the steering compass, to the officer conning the ship.

The helmsman should repeat back every order which is given to him with regard to the helm.

When giving orders for small alterations of course it is usual to name the actual degree which it is desired that the helmsman shall steer; for example, if the helmsman is steering N. 80° E. and it is desired to alter course so as to keep 5° further over to port, the order "Steer N. 75° E." should be given.

If a ship is off her course the fact should be pointed out to the helmsman by saying "You are 3° to the Northward of your course" or "You are 3° to the Eastward of your course," as the case may be, care being taken to indicate that cardinal point to which the ship's head is too near.

When altering course, orders should be given for sufficient helm to cause the ship's head to move immediately. If the alteration of course is small, the helm should be eased as soon as the ship's head is seen to be moving.

To see if the ship is beginning to respond to the helm, the land or the horizon should be watched and the ship's head will be observed to move before there is any indication at the compass. If conning from forward any movement of the ship's head will be detected more quickly by looking aft, and *vice versâ.* If, during an alteration of course, interruptions occur which make it necessary for the officer, who is conning the ship, to direct his attention elsewhere, he should, before leaving the compass, give the helmsman a course on which to steady the ship, thus "Steady her on North East"; and subsequently, he should steady the ship on her proper course by standard compass as soon as possible.

On taking charge of the ship the amount of helm which the ship is carrying should always be ascertained. It is important to remember this, because, if the ship is carrying any helm, it is necessary to allow for it when altering course.

After steadying the ship by the standard compass on the new course, an interval of about five or ten minutes should be allowed to elapse, after which the ship should be steadied again so as to give the compasses time to settle down; this is a valuable check on any mistake that may have been made when the original order "Steady" was given.

When a ship is to be on a course for a few minutes only it is a waste of time to steady her very carefully, for a degree in either direction is of little importance in a distance of a mile or two; but, if the ship is to remain on her course for a considerable time, the greatest care should be taken that the ship is steadied on her course as accurately as possible.

PART III.—THE ATMOSPHERE AND OCEAN.

CHAPTER XIX.

THE WEATHER.

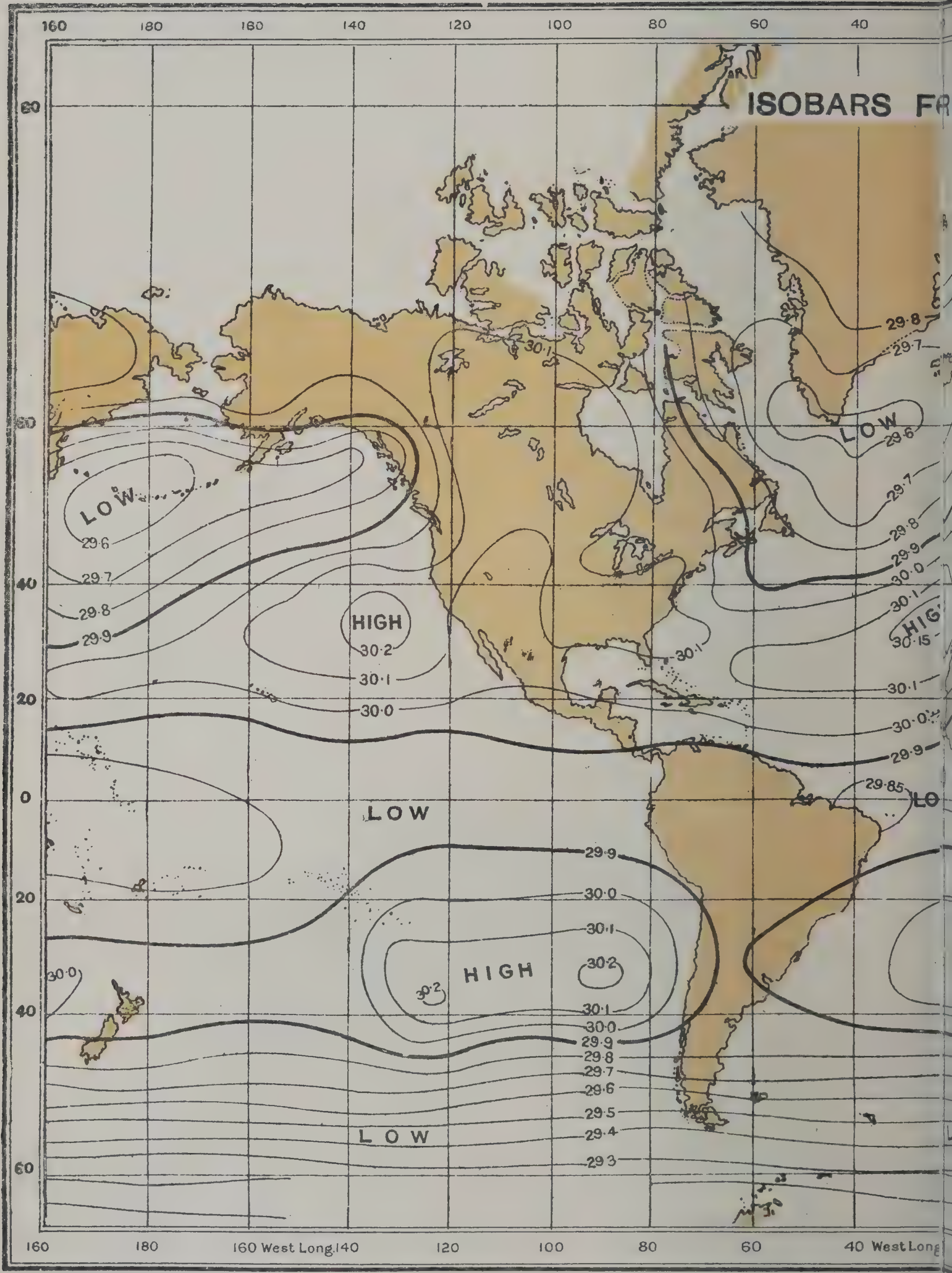
186. The atmosphere.—In Parts I. and II. navigation has been treated without special reference to the movements of the media, the atmosphere and ocean, through which the ship steams. These movements are known as the winds, the rise and fall of the tide, the tidal streams and currents, all of which should be taken into careful consideration in the navigation of the ship (§ 39 and 47), and obviously no movement of the one can take place without some movement of the other. We shall first deal with the weather and forecasting the weather, weather being a general term for the state of the atmosphere with respect to its temperature, pressure, motion, humidity, and electrification.

The atmosphere is a gaseous body surrounding the earth; it is elastic, very sensitive to the action of heat, and is necessarily much denser in the vicinity of the earth's surface than above that level.

Observations have shown that at a height of 7 miles the atmosphere is so rarefied that great difficulty is found in breathing, and at a height of about 40 miles the atmosphere is no longer capable of refracting the sun's rays. The atmosphere may be assumed to extend to about 200 miles above the earth's surface.

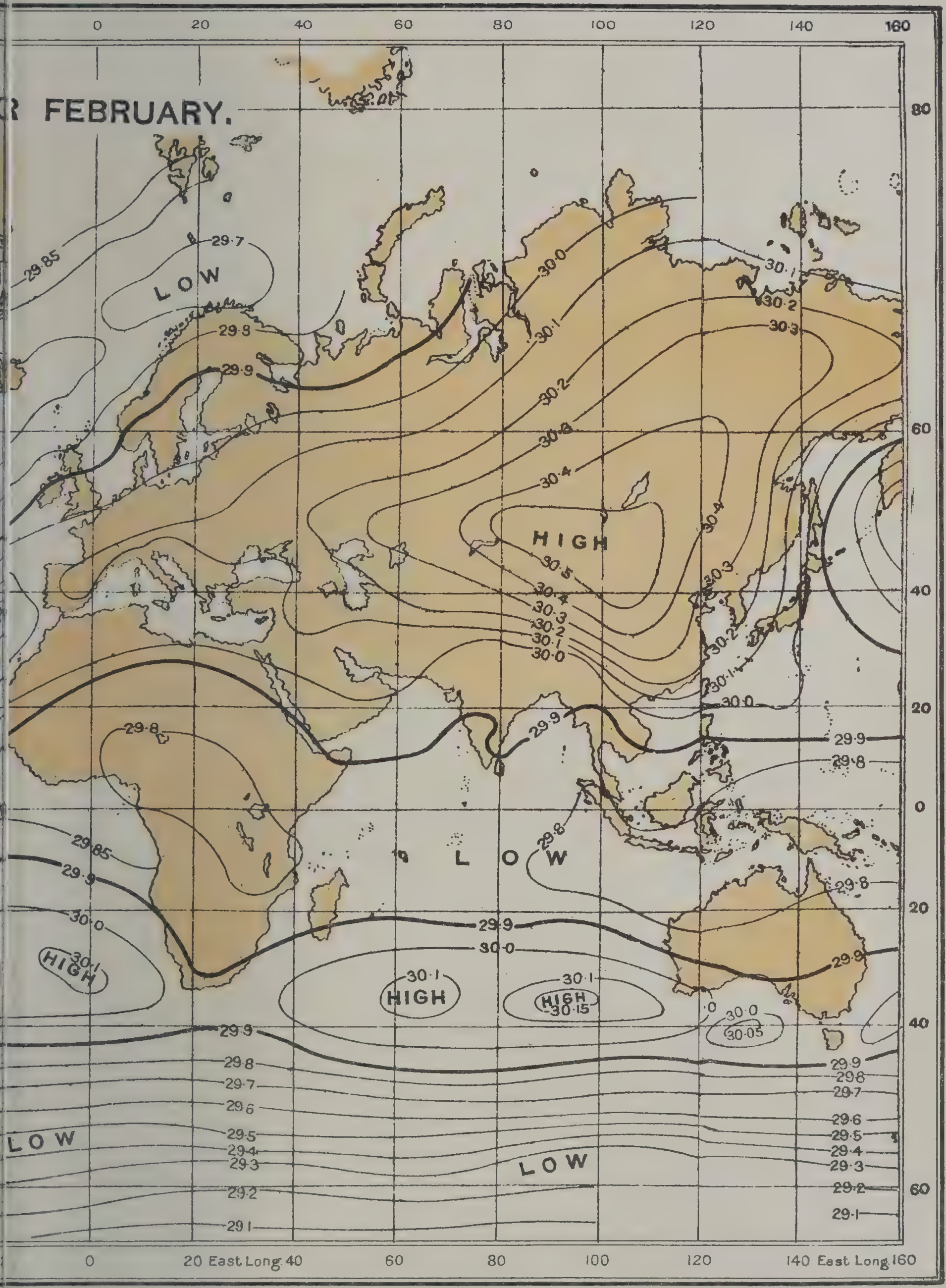
The atmosphere always contains a certain amount of aqueous vapour, although it is seldom, if ever, completely saturated. The ratio of the quantity of aqueous vapour present in the atmosphere at any place to that which it would contain if it were saturated, the temperature remaining the same, is called its humidity. The humidity is measured by means of an instrument called a hygrometer which is described in Part IV.

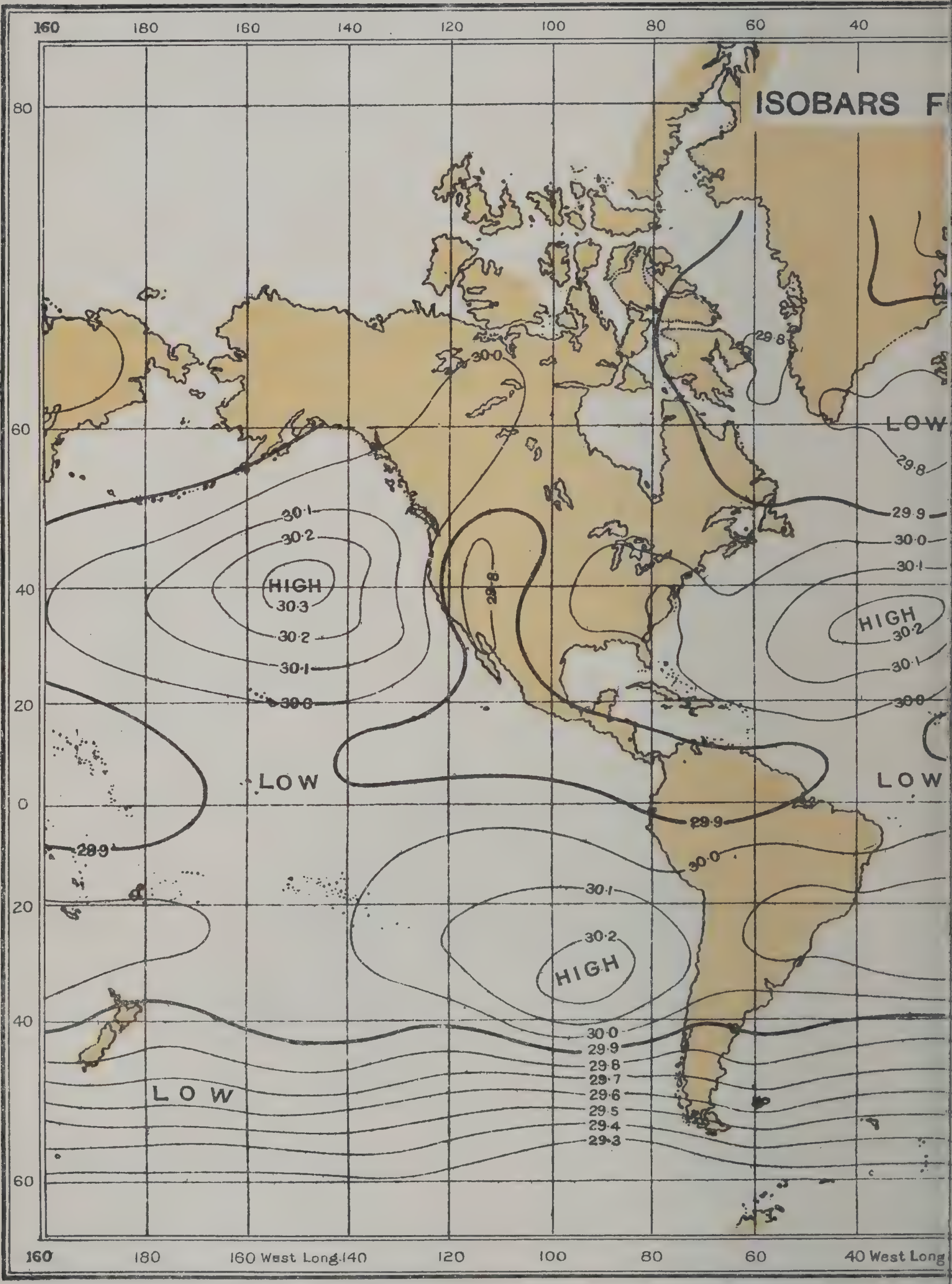
187. The pressure of the atmosphere.—If all parts of the atmosphere had the same temperature, there would be perfect calm and the surface pressure of the atmosphere would be everywhere the same. In consequence of the equatorial regions being at a higher temperature than the polar regions, the atmosphere over the equatorial regions rises and that over the polar regions falls; at the same time the upper strata of the atmosphere flow from the equator towards the poles, and the lower strata flow from the poles towards the equator. If the earth had no rotation on its axis, this circulation would take place in the planes of the meridians. On account of the rotation of the earth, however, rising air is deflected to the Westward, and falling air to the Eastward; also, as will be understood from



38739 405. W.B.&L. 12/1/15

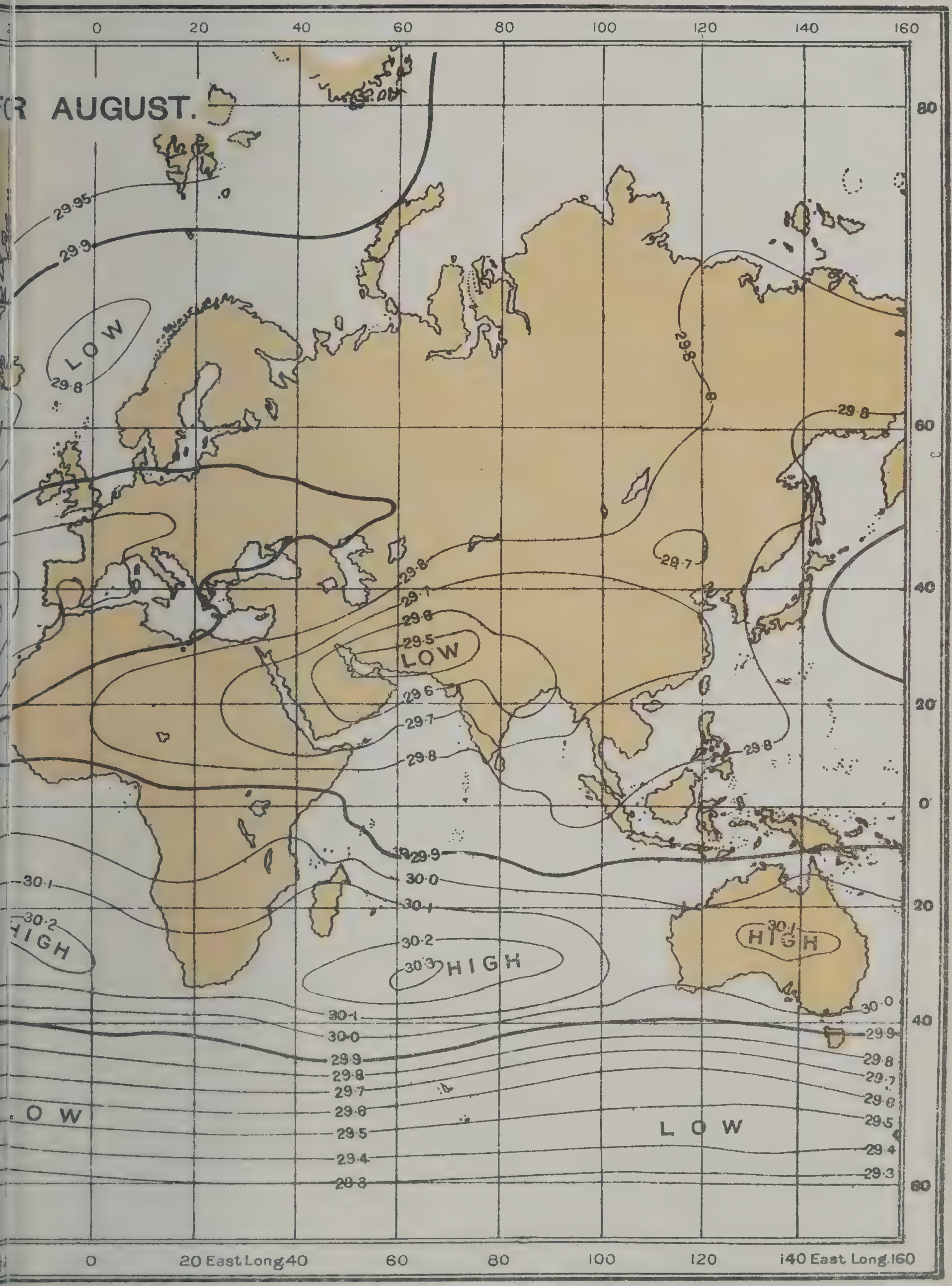
Fig


R FEBRUARY.
0
20
40
60
80
100
120
140
160
80
60
40
20
0
20
40
60
29·85
29·7
LOW
29·8
29·9
30·0
30·1
30·2
30·3
30·4
HIGH
30·5
30·4
30·3
30·2
30·1
30·0
30·4
30·3
30·2
30·1
30·0
30·1
30·2
30·3
29·8
29·9
29·9
29·8
29·8
29·85
29·9
LOW
30·0
30·1
HIGH
29·8
29·9
30·0
30·1
HIGH
30·1
HIGH
30·15
30·0
30·05
29·9
29·9
29·8
29·7
29·6
29·5
29·4
29·3
29·2
29·1
LOW
LOW
29·9
29·8
29·7
29·6
29·5
29·4
29·3
29·2
29·1
0
20 East Long. 40
60
80
100
120
140 East Long. 160



38739 405. W.B & L. 12/1/15

Fig


R AUGUST.
0
20
40
60
80
100
120
140
160
80
60
40
20
0
20
40
60
LOW
LOW
LOW
LOW
HIGH
HIGH
HIGH
29·95
29·9
29·8
29·7
29·6
29·5
30·0
30·1
30·2
30·3
29·4
29·3
20 East Long 40
140 East Long. 160

the following article, air moving from the equator towards a pole is deflected to the Eastward, while in moving towards the equator it is deflected to the Westward.

The result of this circulation of the atmosphere is that in high latitudes the atmosphere is moving faster than the earth's surface, its centrifugal force is consequently increased, and it tends to press on the atmosphere in lower latitudes. Again, the expansion of the atmosphere over the equatorial regions due to the high temperature there causes it to press on that in higher latitudes. The combined effect is to raise the pressure of the atmosphere in about latitude 30°, above that in higher or lower latitudes, and the distribution of the atmospheric pressure is roughly as shown in Fig. 147.

When the temperature at any place is higher than that in the surrounding area, the air over that place expands and rises, and the upper strata flow outwards; the result is that the pressure of the atmosphere at that place is reduced below that in the surrounding area. Due to this cause we may expect that the average pressure at any place will be different in summer and winter. Now the land is more susceptible to changes of temperature than the sea, and so we find that between summer and winter larger differences of pressure occur over the land than over the sea.

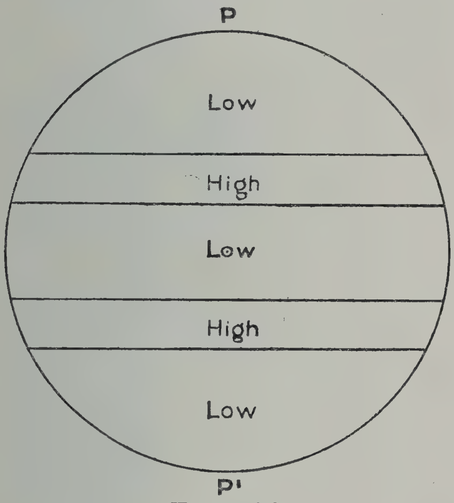


Fig. 147.

The pressure of the atmosphere is measured by means of an instrument called the barometer, in which the pressure is measured by the height, in inches, of the column of mercury necessary to balance it. The barometer is described in Part IV. The average pressure of the atmosphere is about 29·9 inches.

Figs. 148 and 149 show the mean pressure of the atmosphere for the months of February and August respectively, by means of lines drawn through all places where the mean height of the barometer during these months is the same. These lines are called isobars and the charts on which they are drawn are called isobaric charts.

On examining the charts it will be seen that the average pressure conforms fairly closely to what has been said above. Thus, over the equatorial belt the pressure is everywhere relatively low; over the various oceans, between the latitudes of 20° and 40°, the pressure is relatively high, while in latitudes higher than 60° it is low. The most marked difference in the isobars for the two seasons occurs over the continent of Asia, owing to the great susceptibility of the land to changes of temperature, and it will be seen that in the Northern summer and winter the pressures over this area are low and high respectively; this change occurs in a less marked degree over the other continents.

It will be noticed that in several cases the isobars are closed curves, which enclose areas of high or low pressure; the centres of these areas are often referred to as centres of high and low pressure respectively.

188. Cause and direction of wind.—If a place lies between two areas whose barometric pressures are different, the air flows from the area of relatively high pressure to that of relatively low, and wind is experienced at that place.

The velocity of wind depends on the relative pressure in adjoining areas, and is determined by the steepness of the barometric gradient; in other words, the strength of the wind at any place depends on the difference in the heights of the barometer on either side of that place. To compare barometric gradients it is customary to reduce them to hundredths of an inch of mercury per fifteen nautical miles. The steepest gradient ever observed was at False Point in India where it was 238, so that, in a distance of 15 miles, there existed a difference of barometer readings of 2·38 inches.

For purposes of reference a scale, called Beaufort's scale, is used to classify winds of various velocities, and is given in the beginning of the Ship's Log and in the Barometer Manual.

The direction of the wind depends on its velocity due to the barometric gradient, and on that due to the rotation of the earth. If we suppose that the atmosphere is in a state of perfect calm, any small portion of it is moving to the Eastward at the same speed as the locality over which it is situated, so that, although there may be perfect calm over the whole earth, any particular portion of the atmosphere in contact with the earth in latitude L is moving East at 900 cos L knots; this would be the condition of the atmosphere in the absence of disturbing influences.

Let O, Fig 150, be a centre of low pressure in latitude L North where the atmosphere has a speed of 900 cos L knots East and some upward velocity. Let A be a point in a higher latitude L' where the atmosphere is moving East at 900 cos L' knots and, on account of its pressure being higher than at O, is moving South at a certain speed. The horizontal velocity of the atmosphere at A, relative to the centre of low pressure at O, may be found by reducing O to rest and giving the atmosphere at A an additional velocity 900 cos L knots West. Thus, relative to O, the atmosphere at A has a velocity 900 $(\text{Cos } L - \text{Cos } L')$ knots West and a certain speed South; consequently the direction of its resultant speed lies between South and West. Now the direction of the wind is named, not by the

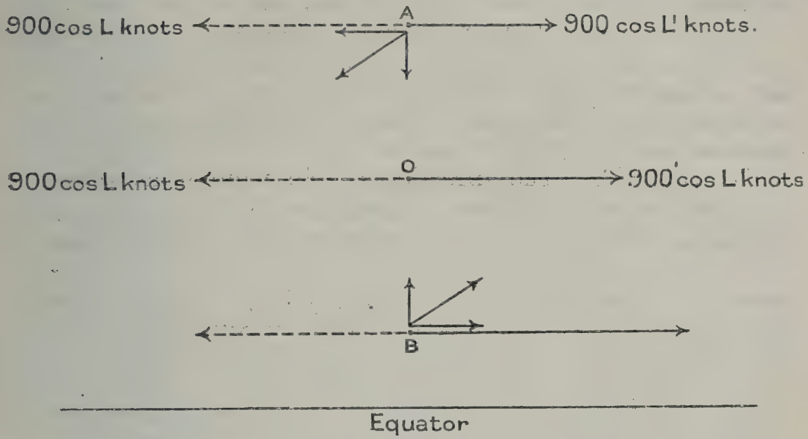


Fig. 150.

direction in which the atmosphere is moving but by the point of the compass from which it has come, so that an observer in the vicinity of *A* experiences a wind from between North and East, that is a North-Easterly wind.

Similarly, if we consider another point *B* in a latitude lower than that of *O*, and where the pressure of the air is greater than that of *O* it will be seen that an observer in the vicinity of *B* will experience a South-Westerly wind.

From a consideration of a large number of points such as *A* and *B*, we conclude, that about the centre of low pressure *O*, there is a circulation of the atmosphere in an anti-clockwise direction, inclined spirally inwards and rising. If the centre of low pressure were in the Southern hemisphere the circulation would be in a clockwise direction. Winds, thus circulating about a centre of low pressure, are called cyclonic winds.

Conversely, if a portion of the atmosphere has its pressure increased above that of the surrounding areas, there is a flow from it to areas of relatively lower pressure. We conclude that, round an area of high pressure there is a circulation of the atmosphere in a clockwise direction in the Northern hemisphere, and in an anti-clockwise direction in the Southern hemisphere, and inclined spirally outwards. Winds, thus circulating about an area of high pressure, are called anti-cyclonic winds.

From the above, it will be seen that at any place there exists a relation between the direction of the wind and the bearing of the nearest centre of low pressure; this relation is known as Buys Ballot's law, and may be enunciated thus :—

In the Northern Hemisphere.	In the Southern Hemisphere.
Stand with your face to the wind, and the barometer will be lower on your right hand than on your left.	Stand with your face to the wind, and the barometer will be lower on your left hand than on your right.

189. Permanent winds. Trades and Westerlies.—Reference to the charts, Figs. 148 and 149, shows that North and South of the equator there are permanent areas of high and low pressure; therefore, in conformity with Buys Ballot's law, it may be expected that about these areas there are winds whose speeds and directions are more or less permanent. Let us consider the effect of the areas of high and low pressure in the North Atlantic. The direction of the wind is as shown in Figs. 151 or 152; between the latitudes of 30° and 10° N. there is a N.E. wind, while in the neighbourhood of the parallel of 40° N. the wind is more or less Westerly. These winds are called the North-East Trade wind (Trades) and the Westerly wind (Westerlies). Similarly it will be seen that there are N.E. Trades and Westerlies in the North Pacific, and S.E. Trades and Westerlies in the Southern ocean. Owing to the comparative absence of land in the Southern hemisphere the Westerly winds blow there with considerable violence, and the region over which they blow, between the latitudes of 40° and 60° S., is called the "roaring forties."

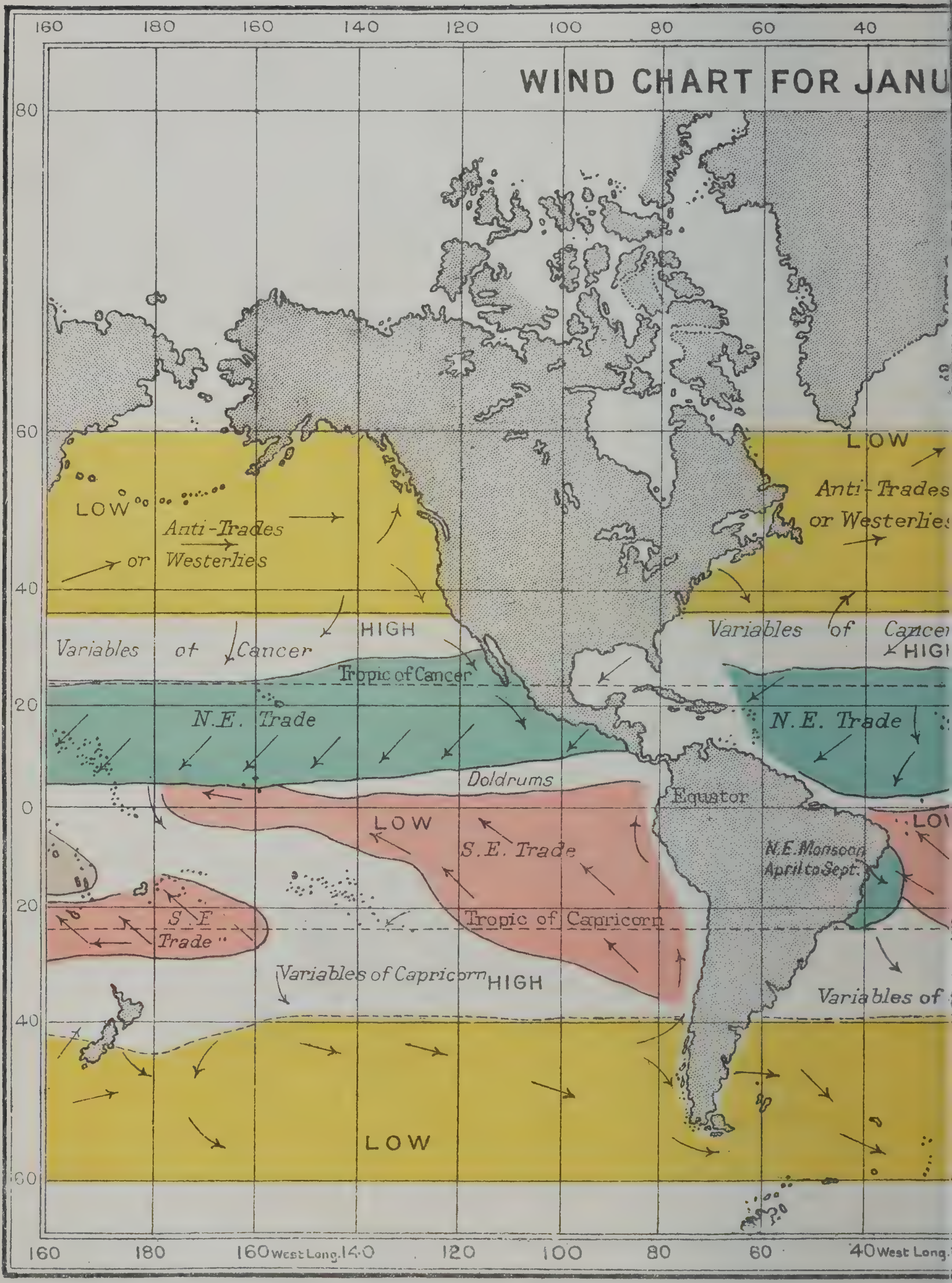
Between the Trades and Westerlies the winds are variable in direction, and the areas over which these variable winds prevail are called, in the Northern hemisphere, the Variables of Cancer and, in the Southern, the Variables of Capricorn; they take their names from those sometimes given to the parallels of latitude of 23° 27′ N. and S. (the Tropic of Cancer and the Tropic of Capricorn). Between the N.E. and the S.E. Trades there is an area of calms which is known as the Doldrums; in this region the weather is generally characterised by clouds and rain, but occasionally by eddies or whirlwinds which form the nuclei of the great tropical storms.

The area of low pressure over the equator, and so the limits of the Trade winds, has a periodic movement North and South corresponding to the movement of the sun in declination. The following table shows the approximate Trade wind limits in the various oceans.

Ocean.	In January.	In July.
North Atlantic	2° N. to 25° N.	10° N. to 30° N.
South Atlantic	0 ,, 30° S.	5° N. ,, 25° S.
North Pacific	8° N. ,, 25° N.	12° N. ,, 30° N.
South Pacific	4° N. ,, 30° S.	8° N. ,, 25° S.
South Indian	15° S. ,, 30° S.	0 ,, 25° S.

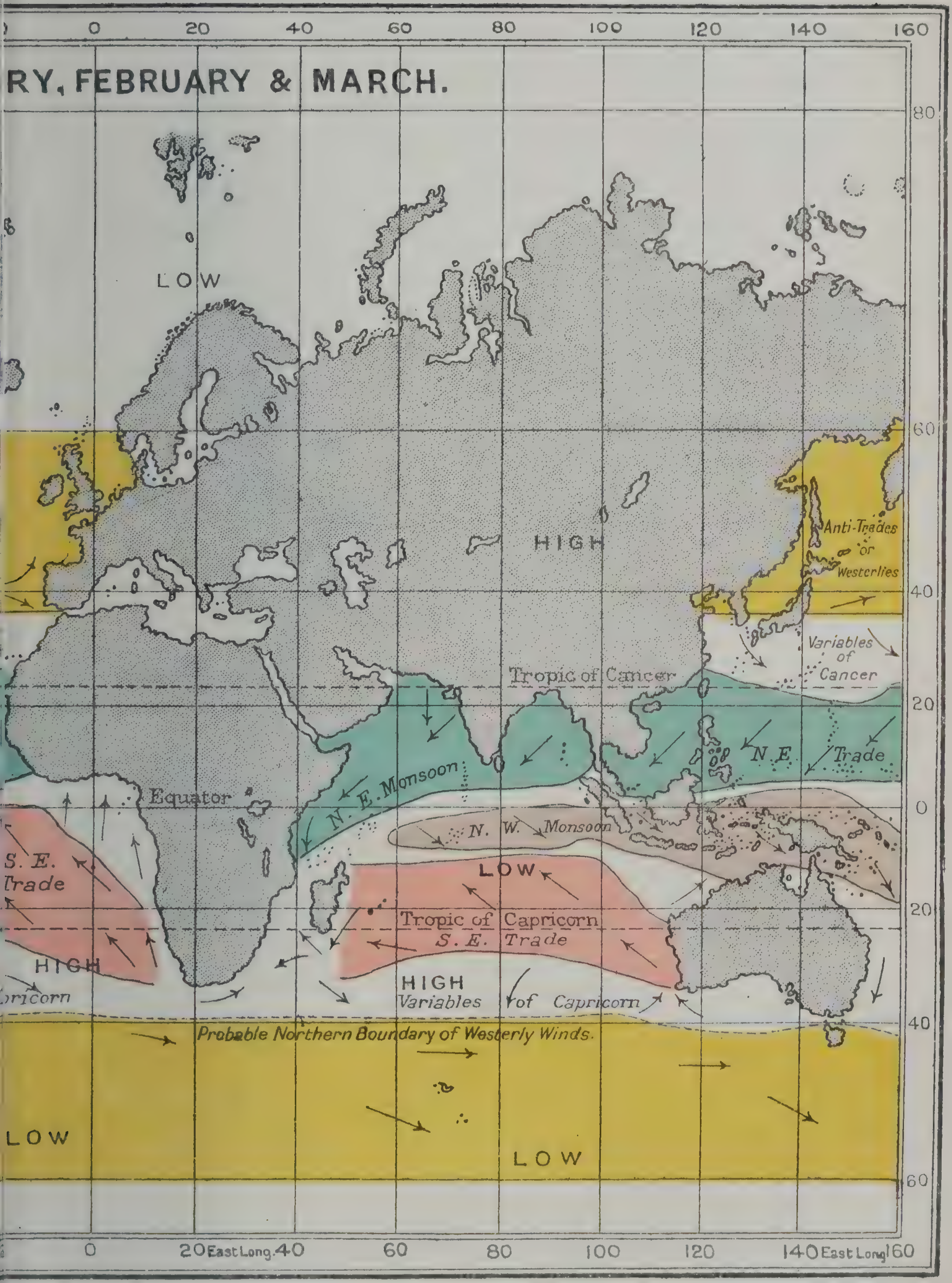
Figs. 151 and 152 show the areas where the Trades and Westerlies prevail.

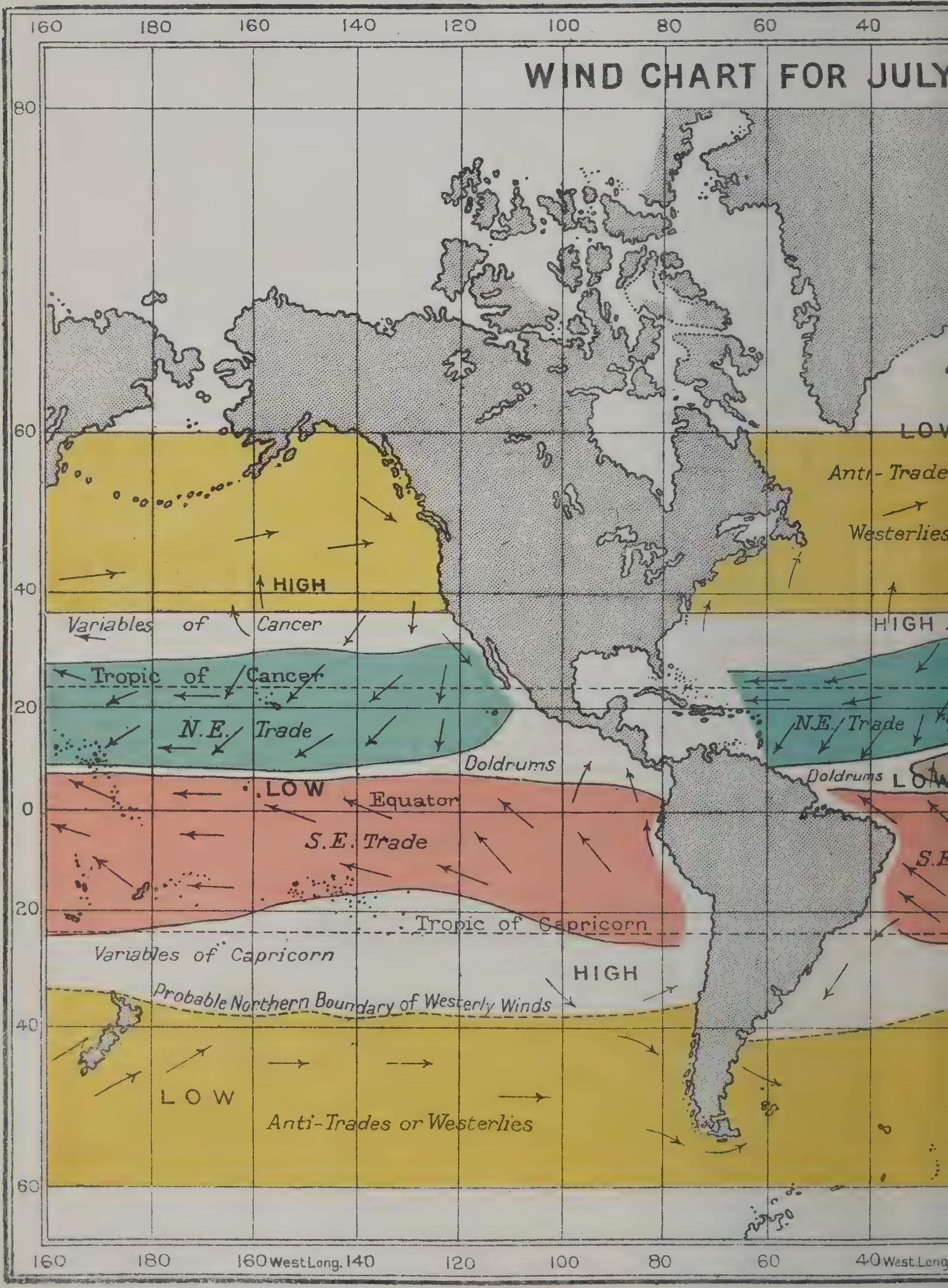
190. Periodic winds. Monsoons.—Let us now consider the effect of the great change of pressure which takes place over the continent of Asia (§187, Figs. 148 and 149). In the Northern summer this continent becomes excessively heated and the pressure is reduced below that of the neighbouring



38739 405. W.B & L. 12/1/15

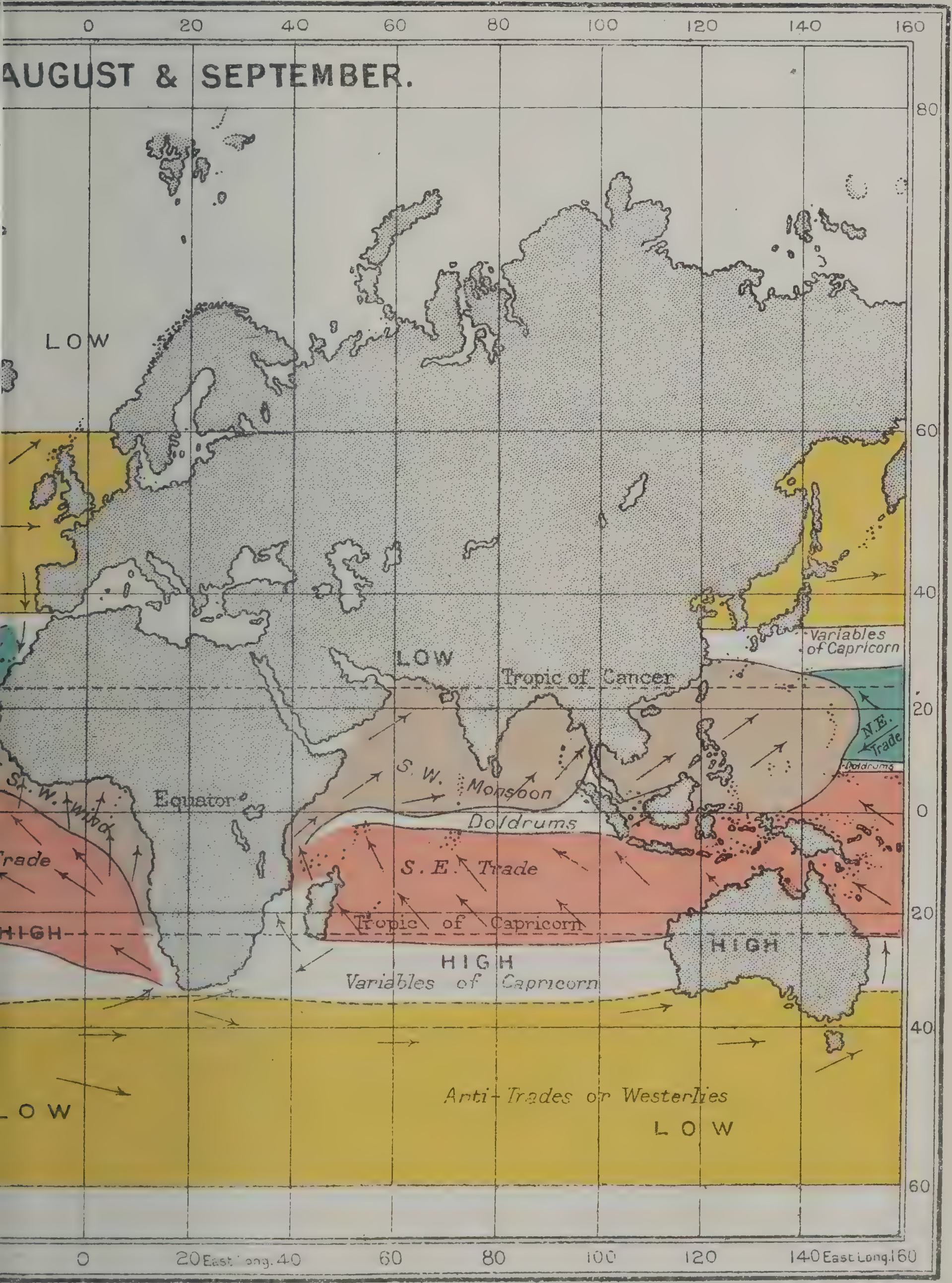
Fig


RY, FEBRUARY & MARCH.
0
20
40
60
80
100
120
140
160
80
60
40
20
0
20
40
60
LOW
HIGH
Anti-Trades
or
Westerlies
Variables
of
Cancer
Tropic of Cancer
N. E. Trade
N. E. Monsoon
Equator
N. W. Monsoon
S. E.
Trade
LOW
Tropic of Capricorn
S. E. Trade
HIGH
HIGH
Variables of Capricorn
pricorn
Probable Northern Boundary of Westerly Winds.
LOW
LOW
20 East Long. 40
140 East Long. 160



36739 405 W.B.& L. 12/1/15

Fi

AUGUST & SEPTEMBER.
0
20
40
60
80
100
120
140
160
80
60
40
20
0
20
40
60
LOW
LOW
Tropic of Cancer
Variables of Capricorn
N.E. Trade
Doldrums
S. W. Monsoon
Equator
Doldrums
S. W. Wind
rade
S. E. Trade
Tropic of Capricorn
HIGH
HIGH
HIGH
Variables of Capricorn
Anti-Trades or Westerlies
LOW
O W
20 East Long. 40
140 East Long. 160

equatorial regions; the result is that a cyclonic wind system, with its centre over Asia, is introduced, and a S.Wly. wind, known as the S.W. Monsoon, prevails over the Indian Ocean and the China Sea. The centre of this cyclonic system is approximately over the Himalayas and, as the barometric gradient becomes steeper as the centre is approached, we find that the S.W. Monsoon in the Indian Ocean blows with great violence, while in the China Sea it is a light wind.

In the Northern winter, however, owing to the continent losing its heat more quickly than the ocean, the pressure of the atmosphere over the continent is raised above that over the neighbouring equatorial regions; the result is that an anti-cyclonic system, with its centre over Asia, is introduced, and a N.Ely. wind, known as the N.E. Monsoon, prevails over the Indian Ocean and China Sea. In this case the centre of the anti-cyclonic system is situated over Eastern Asia, and consequently the N.E. Monsoon in the China Sea blows with considerable violence, while in the Indian Ocean it is a light wind.

From November to March the N.E. Monsoon blows across the equator, and, on account of the change of the speed of the earth's surface in different latitudes, changes its direction and becomes what is known as the N.W. Monsoon which blows from a direction between N.W. and S.W.

The following are the approximate seasons of the Monsoons:—

S.W. Monsoon, March to September.
N.E. and N.W. Monsoons, October to March.

Figs. 151 and 152 show the areas where the Monsoons prevail.

Another example of the effect of land is found in the winds round Australia. In the Southern summer a low pressure exists over Australia due to the heating of the land, and the winds round the continent are therefore cyclonic; in the Southern winter the reverse takes place and the winds are anti-cyclonic.

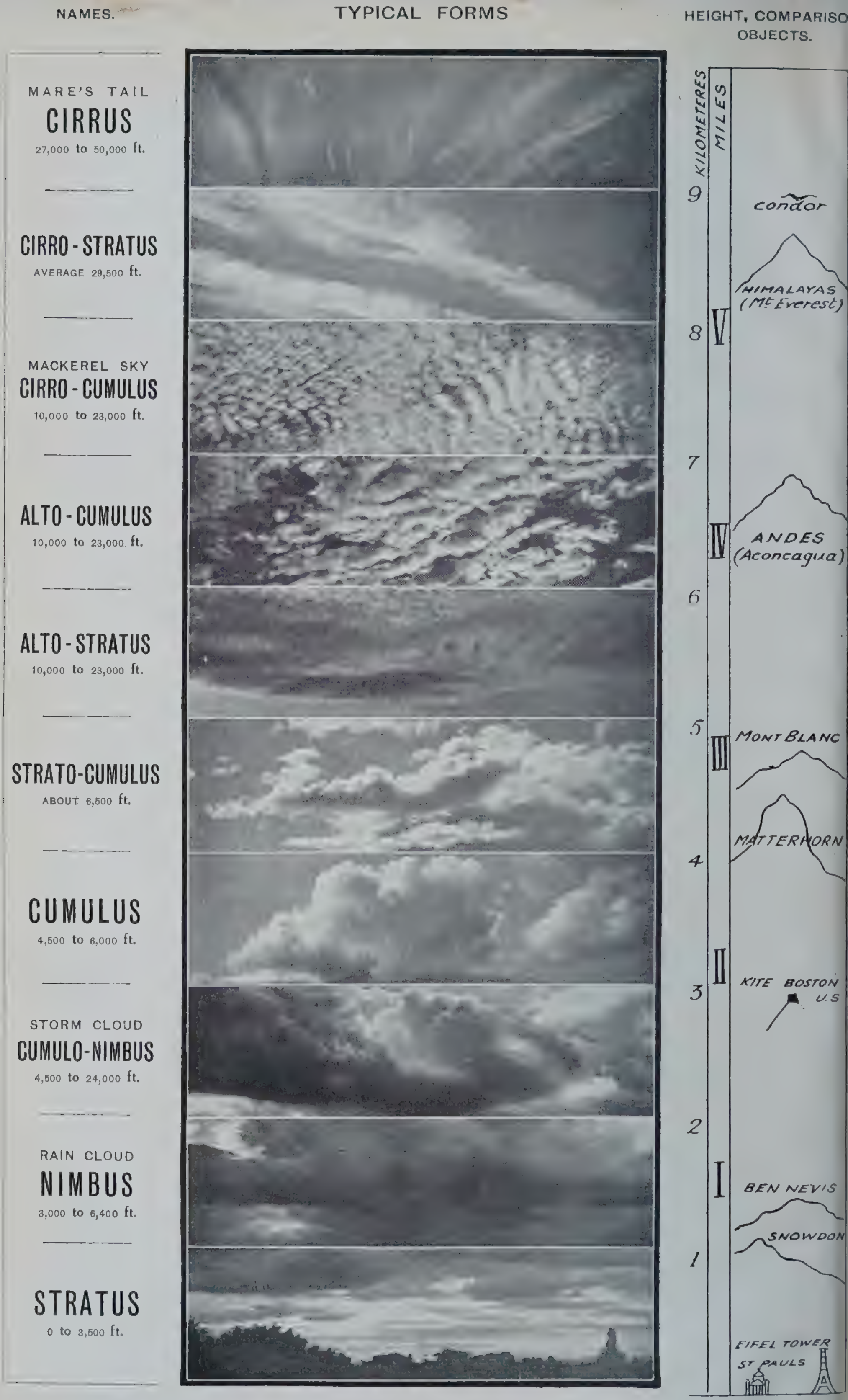
191. Land and sea breezes.—The land and sea breezes which characterise the summer climate of nearly all sea coasts are analogous to the monsoons. The land becomes abnormally heated by day, a low pressure is produced, and a breeze draws in from seaward which continues until the evening. During the night the land loses its heat more rapidly than the water; the daytime conditions are therefore reversed, and a land breeze springs up which continues until the morning.

192. Diurnal variation of the barometer.—Apart from the effects of land, the changes of temperature by day and night give rise to a periodic variation of pressure, which is most marked in the tropics. The barometer rises from about 4^{h} A.M.

to 10^h A.M., falls during the heat of the day until about 4^h P.M., and then rises again until about 10^h P.M., when it once more falls till 4^h A.M. and so on. This diurnal variation has a range of about ·07 of an inch in the tropics, but it is much less outside those regions, where it may still be traced if the mean of a large number of observations is obtained. The regularity of this diurnal variation of the barometer in the tropics is of particular value, because, if the barometer readings on any day do not conform to it, it is certain that some disturbance exists in the neighbourhood, as will be seen in the following chapter (§ 207).

193. Local winds.—On account of varying local conditions, the winds, experienced in different parts of the world have special characteristics and usually have local names. The following table gives the most important local winds and the seasons at which they blow.

Name.	Locality.	Season.	Remarks.
Harmattan	Cape Verde to Cape Lopez.	December, January and February.	A very dry wind from the desert laden with fine sand.
Tornado	West Coast of Africa extending as far South as the River Congo.	March to June. October and November.	A violent squall off shore followed by a downpour of rain.
South-Easter	Cape of Good Hope	October to April	North-Easterly winds very seldom blow at the Cape of Good Hope.
North-Wester	Do. do.	May to September	
Westerly	North Coast of Africa.	Winter.	
Easterly	Do. do.	Summer.	
Scirocco (S.E.)	Malta and Italy	Do.	A hot damp wind.
Gregale (N.E.)	Malta	Winter.	
Bora (N.E.)	Adriatic	Do.	
Etesian (Nly.)	Grecian Archipelago	Summer.	
Mistral (N.W.)	Gulf of Lyons		The most frequent wind, often becomes a gale in winter.
Norther	Gulf of Mexico	September to March.	
Pampero	Rio de la Plata	July to September.	
Easterly	Cape Horn	April to July.	
Williwaws	Strait of Magellan	Frequent	Very heavy squalls.
Norther	Bay of Panama	December to April.	
N.N.W.	Red Sea, Southern part.	June to September.	
S.S.E.	Do. do.	October to May.	
Shamal (N.W.)	Persian Gulf	General.	
Kaus (S.E.)	Do.	December to April	Alternates with Shamal during these months.
Belat (N. to N.N.W.).	Arabia, South Coast	December to March	A strong land wind.
Elephanta	India, Malabar Coast	September and October.	Southerly or South-Easterly gale which closes the South-West Monsoon.
Fort Dauphin (E.N.E.).	Madagascar, South East end.	General.	
Southerly Burster	Australia.		



FORMS, HEIGHTS AND NAMES OF CLOUDS.
FROM PHOTOGRAPHS BY COL. H. M. SAUNDERS.
FIG. 153.

194. Causes of clouds, rain, &c.—When the atmospheric pressure at any place is lower than that of the surrounding areas the air at that place rises, and, if situated over the ocean, the rising air carries with it a large quantity of aqueous vapour resulting from the evaporation of the water. As this column of air and aqueous vapour rises, it expands still further owing to the rarefied state of the upper regions of the atmosphere; this expansion is accompanied by loss of heat, and this loss together with a low temperature over the upper regions causes the aqueous vapour to be condensed; the condensed vapour combined with the multitude of small particles floating in the atmosphere presents the appearance known as clouds.

Two theories of the formation of the clouds have been put forward :—

(1) Condensation by cooling, which is the most general process and is that sketched above.
(2) Condensation by mixing, which takes place when a mass of moist air encounters in its ascent another mass of moist air which is at a different temperature.

The appearance of clouds depends on the way in which they have been formed and on the height at which condensation took place.

Fig. 153 shows the four fundamental forms of clouds, namely :—cirrus, cumulus, nimbus, and stratus, as well as six others, together with their average heights. It is supposed that cumulus, nimbus and rain are due to process (1), that surface fog, which is only cloud in contact with the earth, is due to process (2), and that as regards the other forms of clouds it is impossible to say to which process they may be assigned.

Rain always falls from the nimbus cloud and results from the condensation being so great that water is precipitated. Should the conditions of the atmosphere be such as to condense and freeze the aqueous vapour in its ascent, the precipitation is in the form of hail.

The conditions for the condensation of aqueous vapour in the form of snow are unknown.

Dew is formed when the surface of the earth becomes sufficiently cold to condense the aqueous vapour in the atmosphere which is in immediate contact with it. The temperature at which this occurs is called the dew point. If the dew point is below freezing point, the deposited moisture is known as hoar frost. It is obvious that, when a wind is blowing, neither dew nor hoar frost can be deposited.

When two winds, which are blowing in opposite directions at some distance above the earth's surface, come in contact a vortex is caused and a rain cloud is sometimes brought down to the earth's surface by the rapid gyrations of the air. This presents the appearance of a tapering funnel of water joining the surface of the sea to the cloud, and is known as a waterspout. Waterspouts are common in many parts of the ocean where the climate is warm, and particularly in the Western basin of the Mediterranean Sea. They should not be approached too closely.

195. Causes of fog.—When warm air which is greatly saturated with aqueous vapour passes over cold water, the temperature of the air is reduced, the aqueous vapour is condensed and fog is formed.

When a cold wind blows over warm water the aqueous vapour which is evaporating from the water is chilled with the same result.

When a deep ocean current is opposed by a shoal, such as, for example, the Davis Strait current by the banks of Newfoundland, the cold water from below is driven to the surface, and if its temperature is below dew point fog is formed.

Another cause of fog is the interlacing of currents, the temperatures of which differ considerably, such as the Gulf Stream and the Davis Strait current.

A bank of fog may be driven by the wind to a considerable distance from the place where it originated, provided there is little or no difference in the temperature of the air and surface water, but such fogs soon disappear.

Some fogs have a tendency to lie in a thin stratum which extends only some 30 or 40 feet above the surface of the sea, this probably occurs when the water is colder than the air. It is quite possible to see over such fogs from the masthead, but, on the other hand, there are fogs which have little density till they have attained a height of several feet. Thus we see the necessity of placing lookouts as high up and as low down as possible when a ship is steaming in a fog.

The following table shows the important localities where fogs are frequent and the seasons at which they occur :—

Locality.	Season.
British Islands	At all seasons, but most frequently in the Channel during January and June.
West Coast of Africa, north of the equator.	November to May.
West Coast of Africa, south of the equator.	June to August.
West Coast of North America	Very frequent in the summer.
Banks of Newfoundland	At all seasons, but most frequent in June and July.
Coast of China	January to April.
Japan	April to June.

196. Atmospheric electricity.—The atmosphere is charged with electricity which is generally at a different potential to that of the earth ; the cause of this electricity is uncertain, but there is no doubt that it exists in the minute particles of aqueous vapour which, due to evaporation, are continuously rising. When the difference of potential between a cloud and the earth is sufficiently great a discharge takes place from the former to the latter, and it is accompanied by a brilliant flash known as lightning and by a violent report known as thunder. Thunder and lightning may also be caused by an electrical discharge between two clouds.

Thunder clouds are sometimes as near the earth's surface as 700 feet, but more usually their height is between 3,000 and 6,000 feet. The distance of a thunder storm from an observer may be estimated approximately by noting the number of seconds which elapse between the flash of lightning being seen and the thunder being heard. Remembering that sound travels at about 1,130 feet per second, we have the rough rule—the distance of the storm in cables is about twice the number of seconds observed.

In order to eliminate the possibility of danger in the event of a ship being struck by lightning, lightning conductors are fitted on each mast.

The effect of lightning striking the ship is usually very noticeable at the magnetic compass.

Another effect of atmospheric electricity is the Aurora borealis, which is a brilliant light in the heavens in high North latitudes; it is most frequent at the equinoxes, and least so at the solstices. The Aurora australis is a similar light visible in the Southern hemisphere.

Still another effect is that known as St. Elmo's fire, which is sometimes seen when a discharge of electricity takes place at prominent points, such as the extremities of a ship's yard arms; it appears in the form of small balls of fire and is particularly noticeable on dark tempestuous nights.

CHAPTER XX.

FORECASTING THE WEATHER.

197. The synoptic system of weather analysis.—In the previous chapter the effect of the more or less permanent areas of high and low pressure has been discussed. On account of temporary and local causes small areas of high and low pressure are found which are generally in motion, following more or less the normal direction of the wind, and bringing about variations in the normal weather at the various places which they pass. In this chapter we shall briefly indicate how to forecast the weather at any place on any particular day.

To forecast the strength and direction of the wind and the type of weather likely to be experienced, a system, called the synoptic system, is employed. A synoptic or synchronous chart of a region is one on which is shown the distribution of the various meteorological elements, namely the barometric pressure, the temperatures of the air and water, the strength and direction of the wind, the weather, &c., over the region for the same instant of time. Simultaneous observations, taken at a large number of stations and also on board ships, are placed on the chart, the barometer readings having first been reduced to sea level and to a temperature of 32° F in latitude 45°. The isobars are then drawn, as well as a number of arrows which indicate the direction and strength of the wind. All points at which the temperature is the same are joined by lines called isotherms.

A specimen synoptic chart is shown in Fig. 154.

From a study of a very large number of synoptic charts, more than eleven hundred of which are constructed each year at the Meteorological Office, the following important generalisations have been deduced.

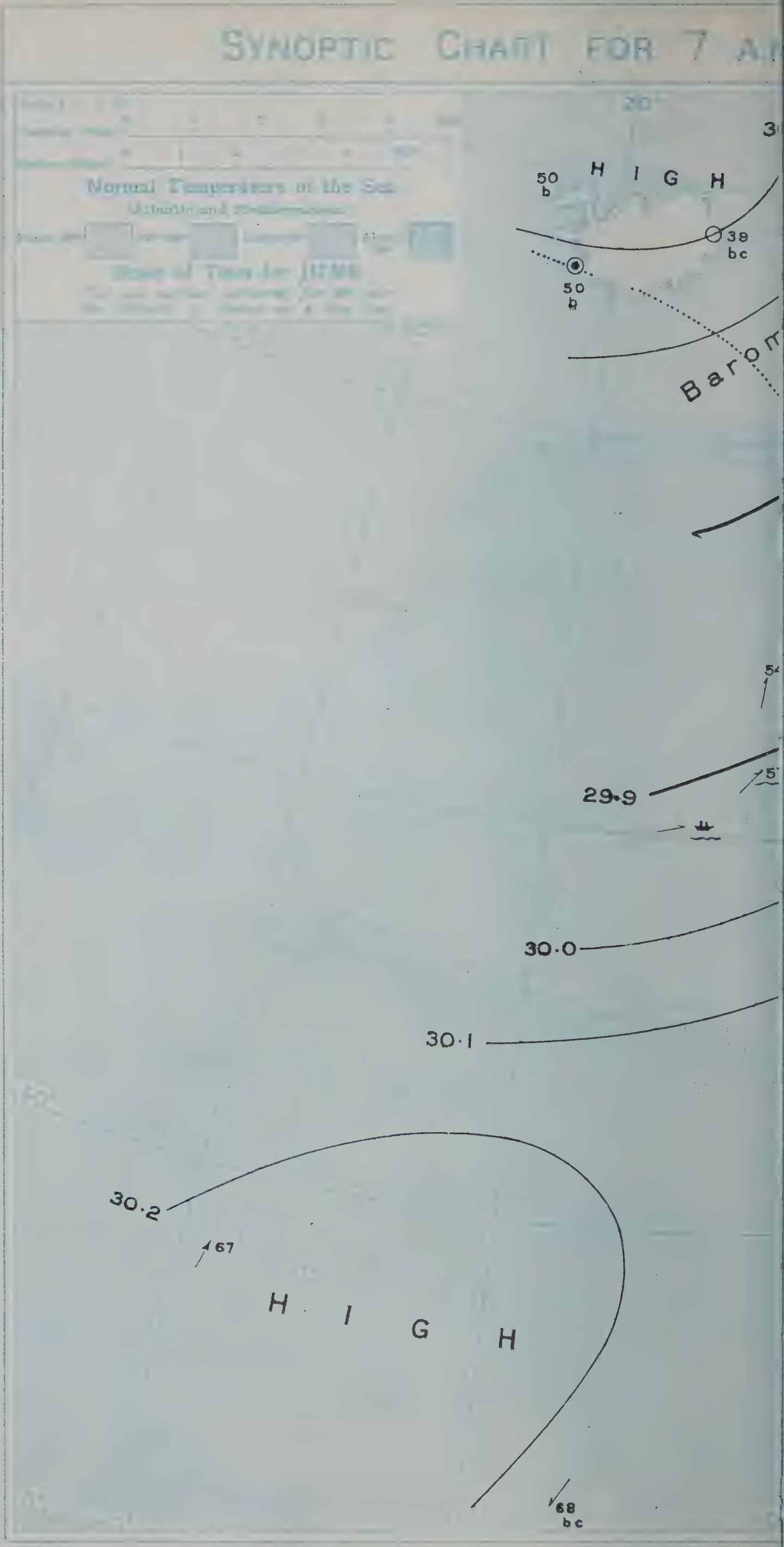
(1) In general, the configuration of the isobars takes one of seven well defined forms.

(2) Apart from the form of the isobars, the wind always takes a definite direction relative to the trend of these lines and the direction of the nearest area of low pressure.

(3) The velocity of the wind is nearly always proportional to the closeness of the isobars, that is to the steepness of the barometric gradient.

(4) The kind of weather, apart from the wind, depends generally on the form of the isobars. Some forms are associated with good and some with bad weather.

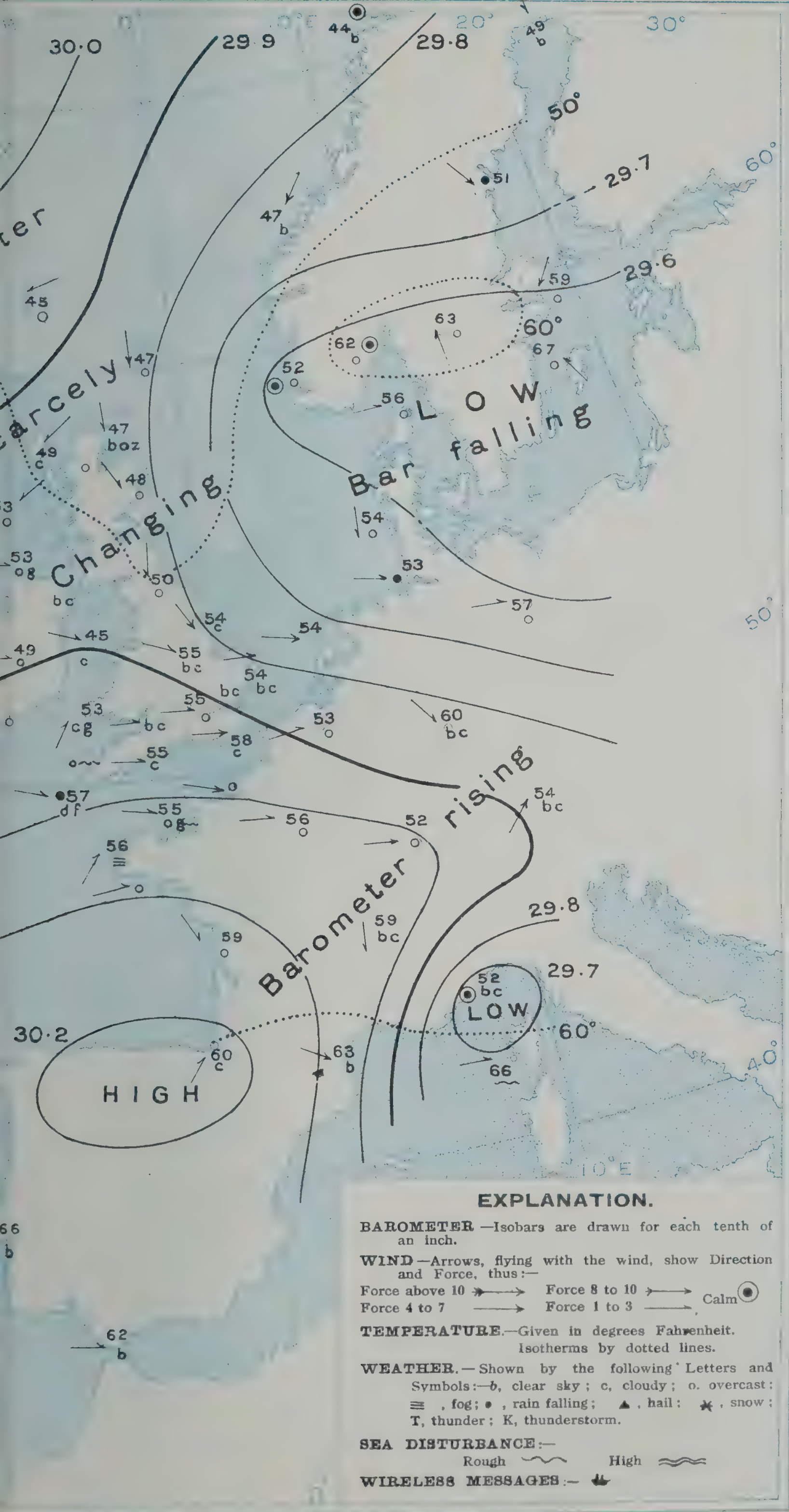
(5) The area mapped out by the isobars is constantly shifting, so that, as it drifts past any place, change of



38739 405 W.B.&L.12/1/15

Fig

FRIDAY 14TH JUNE 1912.



EXPLANATION.

BAROMETER—Isobars are drawn for each tenth of an inch.

WIND—Arrows, flying with the wind, show Direction and Force, thus:—

Force above 10 ⟶ Force 8 to 10 ⟶ Calm ◉
Force 4 to 7 ⟶ Force 1 to 3 ⟶

TEMPERATURE.—Given in degrees Fahrenheit.
Isotherms by dotted lines.

WEATHER.—Shown by the following Letters and Symbols:—*b*, clear sky; c, cloudy; o, overcast; ≡, fog; ●, rain falling; ▲, hail; ✱, snow; T, thunder; K, thunderstorm.

SEA DISTURBANCE:—
Rough 〰 High ≋

WIRELESS MESSAGES:— ✱

weather is experienced. The motion of an area mapped out by isobars follows a certain law which makes forecasting possible.

(6) Sometimes in the temperate zone, and constantly in the tropics, rain falls without any appreciable change in the isobars. This kind of rain is called non-isobaric rain.

198. The seven fundamental forms of isobars.—Fig. 155 shows in a diagramatic form the broad features of the distribution of pressure over the North Atlantic on February 27th 1865. In this Figure the seven fundamental forms of isobars are shown; at the top we see two cyclones, the isobars round each of which are rather close together. Just South of the left hand cyclone the isobar of 29·9 inches forms a nearly circular loop enclosing an area, the pressure over which is lower than 29·9 inches; this is called a secondary cyclone because it is generally secondary or subsidiary to some primary cyclone.

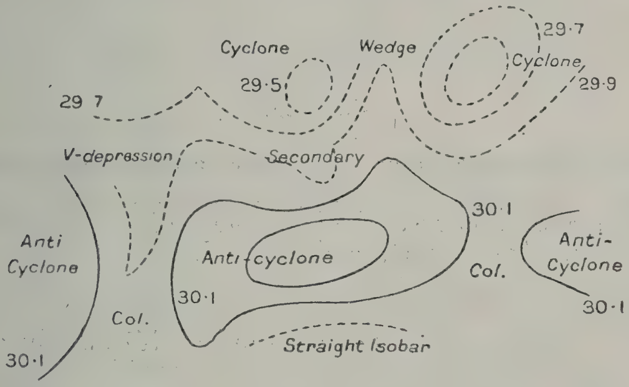


Fig. 155.

Further to the left the same isobar bends into the shape of the letter V and encloses an area of lower pressure; this form is called a V depression. Between the two cyclones the isobar projects upwards and encloses an area of higher pressure; this form is called a wedge.

Below all these there is an oblong area of high pressure, an anti-cyclone, round which the isobars are very far apart. Between the two anti-cyclones there is a neck of relatively lower pressure which is called a col.

Lastly, at the lower edge of the diagram an isobar may be seen which does not enclose an area; this is called a straight isobar.

It has been found that, in the temperate zone (§ 138), cyclones, secondary cyclones, V depressions, and wedges usually move to the Eastward at about 20 miles an hour, while anti-cyclones are often stationary for days.

199. The cyclone.—Fig. 156 shows the kind of weather usually experienced in a cyclone, the small arrows indicating the direction of the wind. The direction in which the cyclone is moving is indicated by the large arrow.

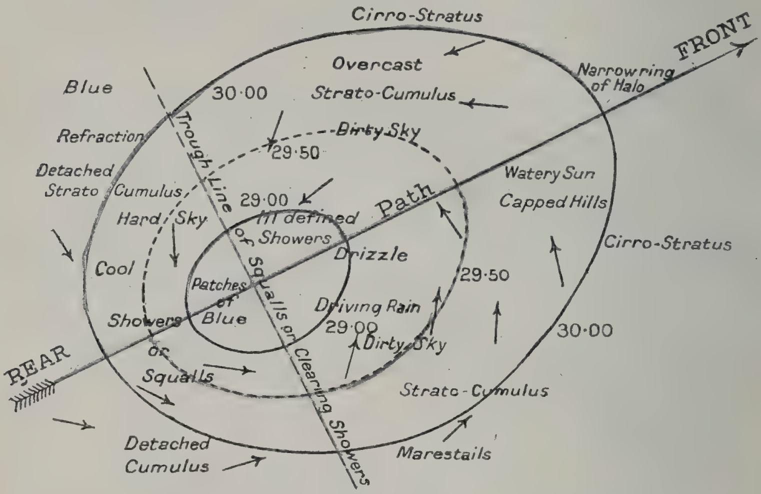


Fig. 156.

It will be noticed that the isobars are oval and not quite concentric, the inner ones being rather in the rear. As the cyclone passes an observer the barometer falls till the centre of low pressure has passed, and then begins to rise; thus if, instead of supposing the observer to be at rest and the cyclone to be in motion, we suppose the observer to be moving across the cyclone as shown in Fig. 157 and the cyclone to be at rest, then the barometer will fall until he arrives at the point *X* when it will begin to rise again; and it will be seen that wherever the path of the observer is with regard to the centre, he will experience some point of lowest pressure such as *X*. The line joining all such points passes through the centre of the cyclone and is approximately a straight line perpendicular to the path. This line is called the trough of the cyclone and is associated with a squall or heavy shower, commonly known as

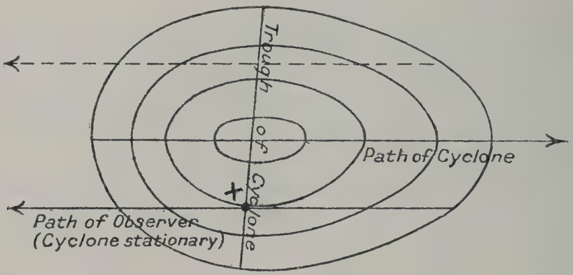


Fig. 157.

the clearing shower, which is very marked in the Southern portions of the cyclones which occur in the North temperate zone.

As mentioned in § 197, the kind of weather experienced and the direction of the wind in a cyclone are approximately always the same, for these elements depend only on the forms of the isobars, while the intensity of the weather and the strength of the wind depend on the closeness of the isobars. The sequence of weather experienced by an observer as a cyclone passes may be seen by reference to Fig. 156.

Wind is said to veer when its direction changes in the same way as the hands of a clock; and it is said to back when it changes its direction in the contrary way to the hands of a clock. Therefore it will be seen that in the Northern hemisphere the wind would veer to an observer situated in the Southern part of a cyclone. If the observer were to the Northward of the path, the wind would back. If the observer were in the path of the cyclone, the wind would remain steady at about South-East and then shift rapidly to North-West as the centre passes, without either veering or backing.

In the centre of a cyclone there is usually a small area of calms with a very heavy dangerous sea.

200. The secondary cyclone.—Fig. 158 shows the kind of weather usually experienced in a secondary cyclone. A secondary cyclone is generally found on the edge of a cyclone but frequently on that of an anti-cyclone. The isobar of 30·1 inches is shown bent downwards, enclosing an area of relatively low pressure, and it will be seen that the gradient between the isobars of 30·1 and 30·0 inches is in consequence very much reduced and therefore the wind inside the bend is very light; conversely, the barometric gradient between the isobars of 30·2 and 30·1 inches is increased and therefore the wind round the edges of the bend is stronger and blows in violent angry gusts and not steadily as in a cyclone.

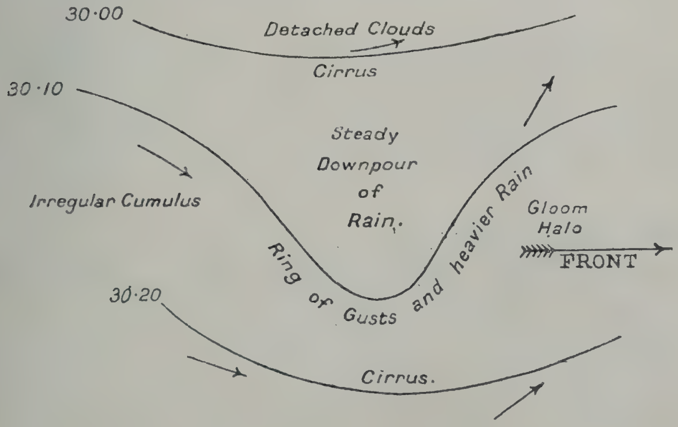


Fig. 158.

The motion of a secondary cyclone is usually parallel to the path of the primary, but when the secondary is formed on the edge of an anti-cyclone its motion is very obscure. Secondary cyclones are associated with a peculiar kind of thunderstorm, a special feature of which is calm and sultry weather.

201. The anti-cyclone.—Fig. 159 shows the kind of weather usually experienced in an anti-cyclone. The isobars are more or less circular and concentric, while the barometric gradient is slight. An anti-cyclone is frequently stationary for days, but sometimes moves on; it more frequently disappears and is replaced by isobars of another form.

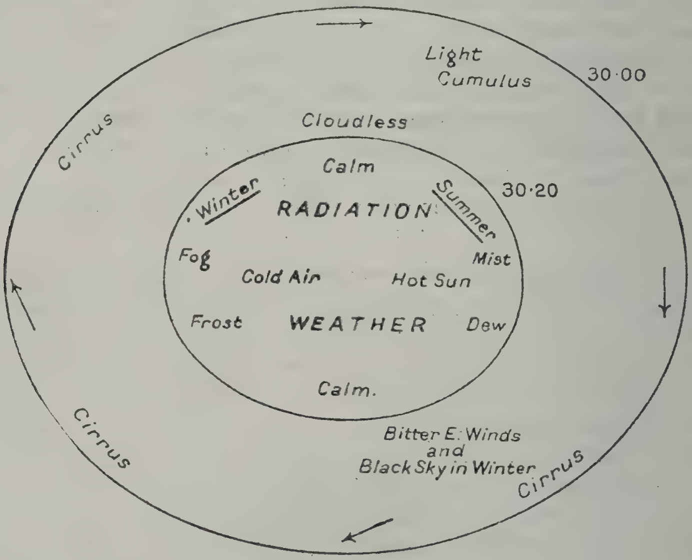


FIG. 159.

The distinguishing feature of an anti-cyclone is radiation weather, the theory of which is that, when the air is still, the heat from the earth's surface radiates into the surrounding atmosphere until the surface becomes sufficiently cold to condense the aqueous vapour in the air, or to form dew or fog.

202. The wedge.—Fig. 160 shows the form of isobars known as a wedge. The isobars of 29·8, 30·0 and 30·2 inches are shown bent upwards between two depressions.

As the two depressions move onwards, the wedge moves on between them, so that there must be a line of stations where the barometer, after it has risen owing to the passing of the first depression, commences to fall owing to the advance of the second depression; this line is called the crest of the wedge. In a wedge the gradient is never steep, so that the wind never rises above a pleasant breeze.

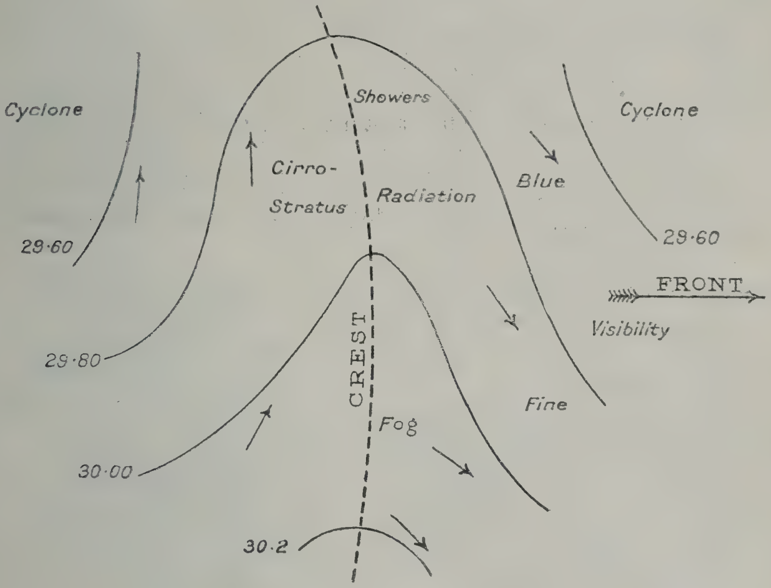


FIG. 160.

203. Straight isobar.—Fig. 161 shows the kind of weather generally associated with straight isobars. The trend of the lines may be in any direction.

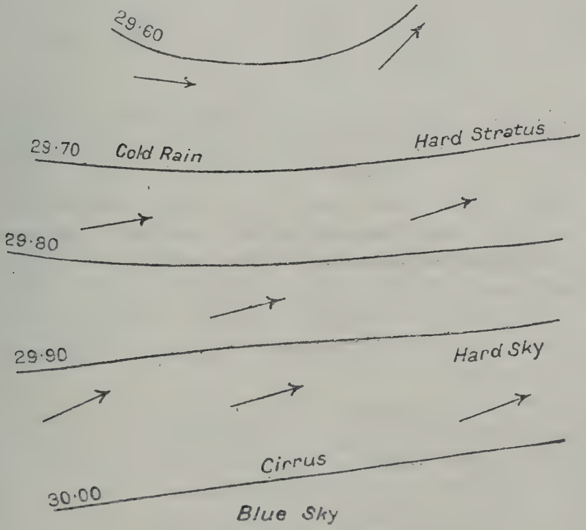


FIG. 161.

In the Figure the barometer is shown high in the South and low in the North. The wind is usually strong or gusty but does not rise to a gale, and when the barometric gradient is steep rain sometimes falls in light showers with a hard sky.

204. The V depression.—Fig. 162 shows the kind of weather usually experienced in a V depression. In the Northern hemisphere the point of the V is generally directed towards the South. The trough (§ 199) is nearly always curved with its convex side towards the East. The wind does not veer in the usual manner, but, as the trough passes over the observer, there is a sudden shift of the wind accompanied by a violent squall.

V depressions are generally formed along the prolongation of the trough of a cyclone to the Southward, or in the col between two anti-cyclones.

There are two kinds of V depressions, that shown in Fig. 162 being the more common in Northern Europe. The other kind differs from this chiefly in the fact that the rain is in the rear instead of in the front of the storm.

From Fig. 162 it will be seen that the trough of a V depression is associated with a line of squalls. As the trough moves broadside on with the V depression to which it belongs, there is a sudden shift of wind (from 8 to 10 points) with a violent squall continually taking place along the trough, so that a long strip of country may be visited by this disturbance at the same instant; this squall, which is characteristic of a V depression, is often called a line squall.

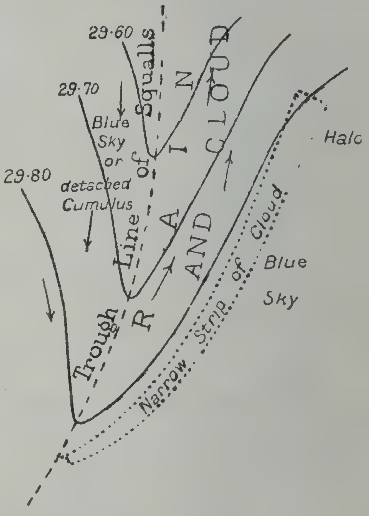


Fig. 162.

205. The col.—The col is merely an area situated between two or more anti-cyclones and of relatively lower pressure. No typical kinds of weather are experienced in a col.

The importance of this form of isobars lies in the fact that, since it lies between two anti-cyclones which are probably stationary, it is a line of weakness along which disturbances may be propagated.

The movement of a cyclone after arriving at a col is uncertain; sometimes it passes through the col, but more frequently the main body of the cyclone is deflected or dies away, while an irregular secondary pushes its way more or less across the col. All that can be said with certainty is that the presence of a col is an indication of unsettled weather.

206. Revolving storms.—Although revolving storms of all kinds are called cyclones by the meteorologist, the very violent ones are known as hurricanes in the West Indies and

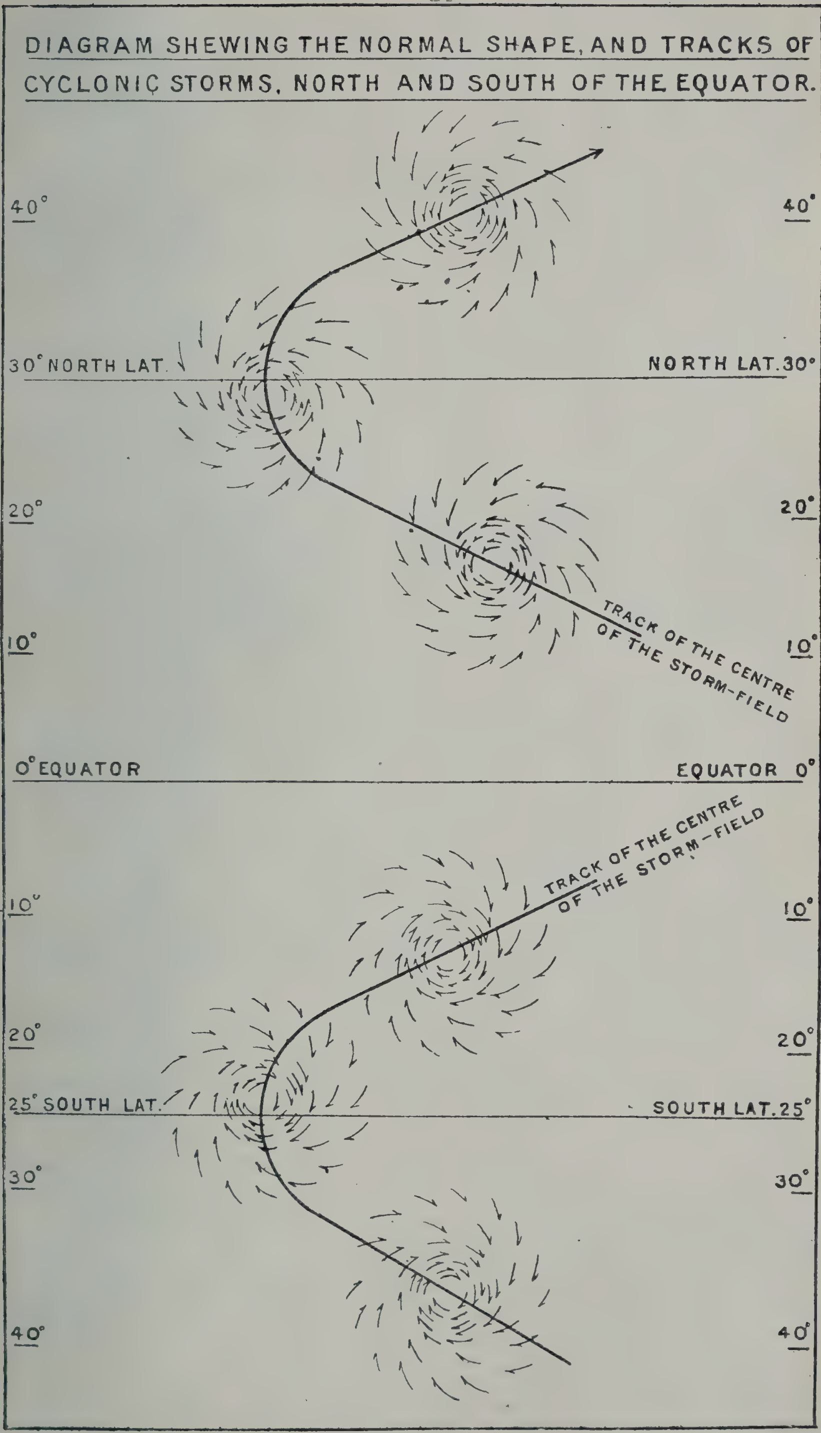


DIAGRAM SHEWING THE NORMAL SHAPE, AND TRACKS OF CYCLONIC STORMS, NORTH AND SOUTH OF THE EQUATOR.
40°
40°
30° NORTH LAT.
NORTH LAT. 30°
20°
20°
TRACK OF THE CENTRE OF THE STORM-FIELD
10°
10°
0° EQUATOR
EQUATOR 0°
TRACK OF THE CENTRE OF THE STORM-FIELD
10°
10°
20°
20°
25° SOUTH LAT.
SOUTH LAT. 25°
30°
30°
40°
40°

Fig. 163.

Pacific Ocean, as cyclones in the Indian Ocean, and as typhoons in the China Sea. Revolving storms are seldom experienced within five or six degrees of the equator and never in very high latitutes; they are most severe in the West Indies, the Southern Indian Ocean (particularly in the vicinity of Mauritius), the Bay of Bengal, and in the China Sea.

In the Northern hemisphere revolving storms occur between July and November, and in the Southern hemisphere from December to May. In the Bay of Bengal and in the Arabian Sea they are most common about the time of the change of the monsoons.

The following table shows the localities and seasons at which revolving storms occur :—

Locality.	Name.	Season.
West Indies - - -	Hurricane	July to November.
North Pacific - - -	Hurricane	July to October.
China Sea - - - -	Typhoon	July to November.
Arabian Sea and Bay of Bengal.	Cyclone	April and May. October and November.
South Indian Ocean - -	Cyclone	December to April.
South Pacific - - -	Hurricane	December to April.

The following rhyme may be of use in remembering the seasons at which the West Indian Hurricanes may occur :—

"June—too soon,
July—stand by,
August—look out, you must,
September—remember,
October—all over."

When interpreting this rhyme it must be borne in mind that many hurricanes occur in October, and the hurricane season cannot be said to be over till November.

These storms, which originate in the tropics, at first travel about W.N.W. or W.S.W. at speeds varying between 50 and 300 miles a day; they gradually curve to a more polar direction along the edge of the great ocean anti-cyclones (Figs. 148, 149) which generally lie between the latitudes of 20° and 40°. They may continue travelling in a North-Westerly or South-Westerly direction over the continents, but more frequently they curve to the North-Eastward or South-Eastward, along the polar edge of the ocean anti-cyclone, and eventually may travel to the Eastward with the general movement of the atmosphere, or die out on meeting some high pressure area.

The path of a storm is the track followed by its centre. Fig. 163 shows the normal paths of revolving storms from the tropics into the temperate zones. It will be noticed that in the Northern hemisphere the direction of the path changes in about Latitude 30° and in the Southern hemisphere in about Latitude 25°.

The point of the path at which the direction changes is called the cod of the storm.

The trough of the storm is the line through the centre at right angles to the path.

That part of the storm which is on the right hand of the path in the direction of advance is called the right-hand semicircle; the corresponding part on the left hand is called the left-hand semicircle.

The trough of the storm divides each semi-circle into two quadrants, called the front and rear quadrants.

The right-hand semicircle is called the dangerous semicircle in the Northern hemisphere, and the left-hand semicircle is called the dangerous semicircle in the Southern hemisphere; these names arise from the fact that a vessel, if situated in the fore part of the semicircle, may possibly be drawn across the path of the storm. It will be seen that the dangerous semicircle is always on the inside of the curve which is the path of the storm.

The diameter of the area covered by a revolving storm at a particular instant has been found to vary from 20 miles to several hundreds.

In the Atlantic and South Indian Oceans these storms originate to the Eastward in about latitude 10°; those of the Bay of Bengal originate near the Andaman Islands, and those of the Arabian Sea near the Laccadive Islands. The last two generally travel to the West and North-West, while those of the Bay of Bengal sometimes cross India.

The typhoons of the China Sea generally move in a Westerly or North-Westerly direction at first; they then curve to North and then to North-East. In the earlier part of their season they often blow right home to the coast of China, whereas late in the season they often curve off before reaching the coast, passing outside Japan and dying away in the Pacific.

The rate of progression of revolving storms varies, but the average speeds in the various localities are:—

West Indies - - -	300 miles per day.
Arabian Sea - - -	200 ,, ,, ,,
China Sea - - - -	200 ,, ,, ,,
Bay of Bengal - - -	200 ,, ,, ,,
South Indian Ocean - -	50 to 200 miles per day.

At the beginning and end of the hurricane season in the South Indian Ocean a large proportion of cyclones are either stationary or move very slowly.

The approximate average tracks of the revolving storms in the various oceans are shown on the pilot charts.

207. The indications of the approach of a revolving storm.—The approach of a revolving storm is indicated by:—

(1) A falling barometer, or an interruption of the usual diurnal range (§ 192).

(2) An ugly threatening appearance of the weather and a rising gusty wind.

(3) A long heavy swell or confused sea, which is not caused by the then prevailing wind, but generally comes from the direction in which the storm is approaching.

208. Rules for determining the path of and avoiding a revolving storm.—When in the region and in the season of revolving storms be constantly on the lookout for the indications just mentioned, and carefully observe and record the barometer. If there is any indication of the approach of a storm it is necessary to know :—

(1) The direction of the centre of the storm.

(2) In which quadrant of the storm the vessel is situated.

In order to ascertain these the observer must be stationary, so that it is necessary to stop or heave to. In a sailing vessel it is safer to assume that one is in the dangerous semicircle, in which case the ship should be hove to on the starboard tack if in the Northern hemisphere, and on the port tack if in the Southern hemisphere; by so doing, every change in the direction of the wind will be from some direction further from ahead, as may be seen from Fig. 163, and so the danger of being taken aback will be guarded against.

To find the bearing of the centre.—To find the bearing of the centre the observer should face the wind, and the centre of the storm will be from 12 to 8 points on his right hand in the Northern hemisphere, and on his left hand in the Southern hemisphere. At the beginning of a storm 12 points should be allowed; when the barometer has fallen three-tenths of an inch 10 points should be allowed, and when it has fallen six-tenths or more 8 points.

To find in which quadrant the ship is situated.—To find in which semicircle the ship is situated the observer should face the wind; if it shifts to the right she is in the right-hand semicircle, and if it shifts to the left she is in the left-hand semicircle. To find in which quadrant the ship is situated he should note whether the barometer is rising or falling; if it is falling she is before the trough of the storm, and if it is rising she is in the rear of the trough.

The centre of a revolving storm is the region of greatest danger; near it the wind is strongest, the direction of the wind changes suddenly, and the sea is most turbulent. If the wind remains steady in direction but increases in strength with a falling barometer, the ship is in the direct path of the storm.

These rules hold good for both hemispheres.

To avoid a revolving storm.—If it has been found that the ship is in the path of the storm she should run with the wind on the starboard quarter in the Northern hemisphere, and with the wind on the port quarter in the Southern hemisphere, until the barometer has ceased to fall.

If it has been found that the ship is in the dangerous semicircle she should remain hove-to until the barometer begins to rise.

If it has been found that the ship is in the safe semicircle she should run with the wind on the starboard quarter in the Northern hemisphere, and with the wind on the port quarter in the Southern hemisphere, until the barometer begins to rise.

Careful note should be taken of any land that may be in the vicinity, as it may be possible to run into harbour or under the lee of land for shelter. In the Sailing Directions for the coasts of China a list of ports, called typhoon harbours, is given; in any of these a ship may safely ride at anchor during a typhoon.

It has been stated by Professor Meldrum that in the South Indian Ocean it is often difficult to ascertain the bearing of the centre, owing to the difficulty of knowing whether the wind is a strong Trade wind or part of a storm. When the wind has shifted decidedly to East or South the centre may be approximately determined. In such a case, if the wind shifts from South-East directly to South, the ship should run to the North-West; if the wind remains steady at South-East and the barometer falls, the ship is in the path of the storm and should run to the North-West.

It has also been stated that in cyclones of the South Indian Ocean, North-Easterly and Easterly winds often, if not always, blow towards the centre.

209. Weather in the British Islands and North Sea.—The British Islands and North Sea being situated between the parallels of 50° and 60°, Westerly winds prevail (§ 189), and Westerly gales are more prevalent than any other; they are most frequent in the winter months, between October and March, and often last three or four days; during May, June, and July they are rare. South-Westerly gales are most dangerous in the Eastern part of the channel, for when accompanied by rain they sometimes veer suddenly to North-West or North and cause a heavy sea.

Winds from North to North-East are sometimes strong but seldom become gales in the central portion of the channel, except on the coast of France; they do not usually last more than a day or two and the wind does not shift as it does with Westerly winds.

In the channel, during winds from between North-North-East and East, the land is generally covered with a white fog which resembles smoke.

Easterly winds are most common in the spring. South-Easterly winds accompanied by rain and a falling barometer almost always become gales. Moderate winds from North-West to North-East bring fine weather.

During summer land and sea breezes frequently occur; at such times it usually falls calm at dark and a heavy dew is formed. Little or no dew is a sign of an impending change in the weather.

Prolonged calms are of rare occurrence, even in summer; they are generally precursors of bad weather, of which there are no more certain indications than swell in the offing and surf on the coast during a calm.

The usual signs of an approaching cyclone are the wind backing to some point between South and South-East, and high cirrus clouds approaching from some Westerly point followed by cirro-stratus (§ 194), in which latter mock suns and halos round the moon are seen.

The tracks followed by cyclones which pass over the British Islands are erratic, owing to the fact that they are often deflected from their course by the land. Those which pass between the Hebrides and Iceland generally pursue a regular course to the North-East, and if the position of the area of high pressure, as given in the daily weather reports signalled to all H.M. Ships, is studied, it is possible to forecast the path of a cyclone with a fair degree of accuracy. It is exceptional for the centre of a cyclone to pass so far South as the English channel. Cyclones which pass over the British Islands almost invariably pursue an Easterly course. The wind therefore in these cyclones, wherever their centres may be, provided that they are North of the observer, begins between South and South-East and after a number of hours veers to some point between South and West.

It has been found from a large number of observations that when the wind is between South and South-East the direction of the centre is about 120° from the direction of the wind, so that if the observer faces the wind the centre will be about 120° to his right (§ 208).

When the wind has veered to some point between South-South-West and West the bearing of the centre is about 100° from the direction of the wind.

The following table gives the mean angle between the direction of the wind and the bearing of the centre of the cyclone, for those cyclones which pass over or near the British Islands:—

Direction of Wind.	Mean Angle.	
	Centre, close.	Centre, at a distance.
N. - - - -	115°	118°
N.E. - - - -	127	128
E. - - - -	122	132
S.E. - - - -	125	126
S. - - - -	116	114
S.W. - - - -	106	104
W. - - - -	103	101
N.W. - - - -	99	100

The following table, which has been made out for different months, gives the mean rate of progression of the cyclones which pass over, or near, the British Islands :—

Month.	Miles per hour.	Month.	Miles per hour.
January	17·4	July	14·2
February	18·0	August	14·0
March	17·5	September	17·3
April	16·2	October	19·0
May	14·7	November	18·6
June	15·8	December	17·9

210. Storm signals.—As explained in § 197, synoptic charts are prepared daily from observations taken at a large number of stations in the British Islands, Iceland, and on the continent as well as on board ships at sea. From a study of these charts the Meteorological Office issue daily weather notices which, besides being signalled to H.M. Ships, are also transmitted by various commercial wireless telegraphy stations. Whenever bad weather is approaching the British Islands, information is telegraphed to numerous storm signal stations directing them to hoist a certain signal, in order to warn passing vessels of the weather that may be expected in their particular localities.

Similarly, storm signal stations in other countries display storm signals from information received from their own National Meteorological Departments. In the majority of countries these signals refer to disturbances which are expected in the vicinity of the signal station displaying the signal, but in some cases, notably on the coasts of China, the signals indicate the position and track of a disturbance.

The majority of European countries use the same code, called the international code, which is given below. Information relating to the code of signals used at any place will be found in the Sailing Directions for that place.

International code.

The signal consists of the display of one or two cones, and the signification of each signal is as follows.

Single cone, point upwards.—Gale commencing with wind in the North-West quadrant.

Single cone, point downwards.—Gale commencing with wind in the South-West quadrant.

Two cones, one above the other, both points upwards.—Gale commencing with wind in the North-East quadrant.

Two cones, one above the other, both points downwards.—Gale commencing with wind in the South-East quadrant.

Two cones with their bases together.—Hurricane. (Wind force 12 Beaufort's scale.)

The above code is about to be adopted (1914 to 1915) for use in the British Islands, but until any signal station is equipped with the necessary appliances, the code shown below, which has been in use in the British Islands for many years, will continue to be used.

One cone, point upwards (North cone).—Strong wind or gales from North or East, backing through North.

One cone, point downwards (South cone).—Strong winds or gales from South or East, veering through South to South-West.

211. Forecasting by a solitary observer. — When attempting to forecast the weather in a ship at sea, the observer has at his disposal :—

(1) The daily weather notice, from which he can probably find the position, at some previous time, of the centres of the principle areas of high and low pressures in the vicinity.
(2) His knowledge of the present state of the weather and the information recorded in the log during the preceding few days.
(3) The movements of the barometer as recorded in the log, or by the trace drawn by a barograph.
(4) Wireless reports as to the weather and movements of the barometer, which may be received from other ships.

With this information available the principles set forth in this chapter should be followed as closely as possible, that is, the movement of any disturbance mentioned in the daily weather notice should be estimated from the knowledge of its probable track and from (2), (3) and (4); this, however, is rendered difficult by the movement of the ship, for if a ship is steaming directly towards the centre of a depression the barometric gradient appears to be much steeper than is really the case, and if she is steaming away from and being overtaken by a depression the gradient appears slighter. All that we can safely deduce from the movements of the barometer is that, if the rate at which the barometer is falling increases, the gale will probably become worse ; and if the rate of fall decreases, the gale will probably moderate. In this connection we see the value of the instrument, called a barograph, which draws a trace of the readings of the barometer ; Fig. 164 shows a specimen trace. It will be seen that when the barometer is rising or falling uniformly, the trace becomes a straight line ; if, however, the rate of rise or fall changes, the trace becomes either convex or concave to the direction of the base line according as the rate increases or decreases. Therefore the shape of the trace, whether straight, convex, or concave is independent of whether the barometer is rising or falling, but simply depends on the rate of change of the rate of rise or fall. Now, as explained in § 188

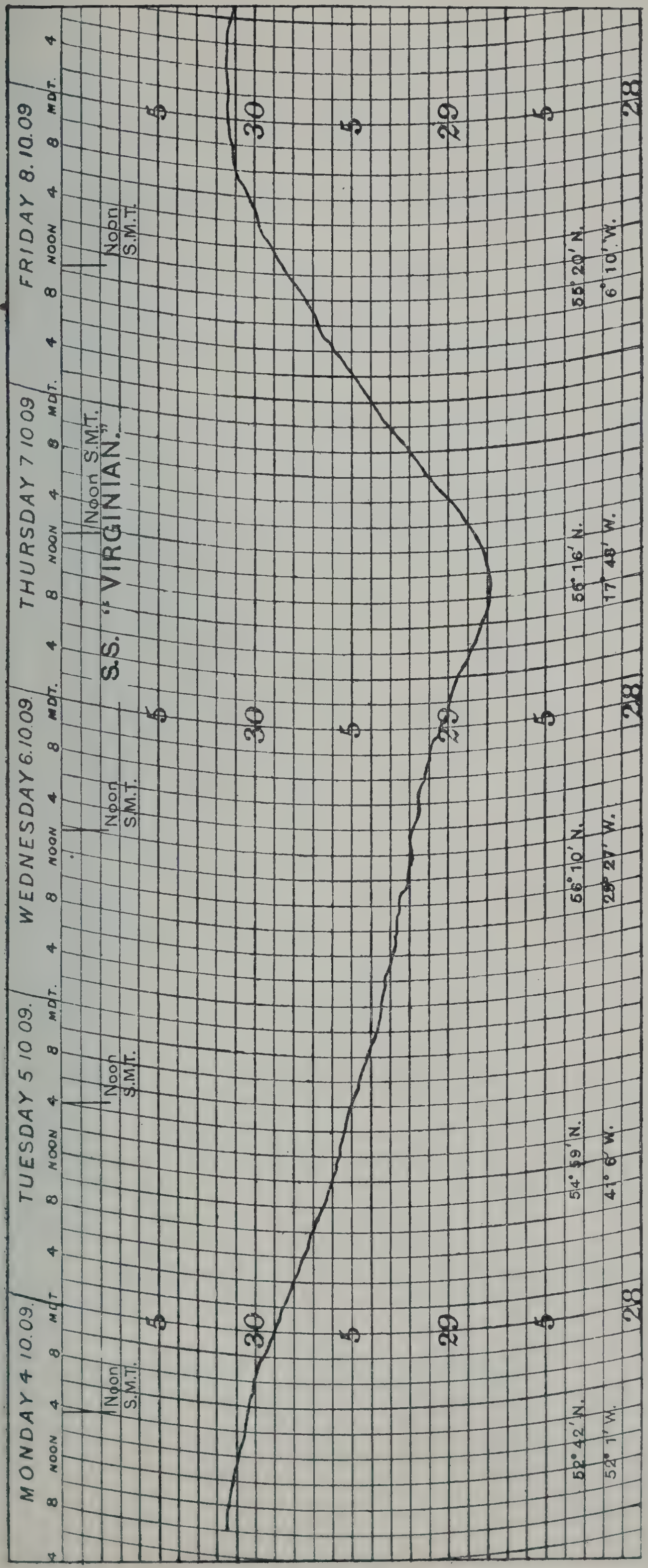

MONDAY 4 10.09.
TUESDAY 5 10 09.
WEDNESDAY 6.10.09.
THURSDAY 7 10 09
FRIDAY 8.10.09
8 NOON 4 8 MDT 4
S.S. "VIRGINIAN."
Noon S.M.T.
52° 42' N.
52° 1' W.
54° 59' N.
41° 6' W.
56° 10' N.
29° 27' W.
56° 16' N.
17° 48' W.
55° 20' N.
6° 10' W.
30
29
28
5

Fig. 164.

the velocity of the wind is proportional to the slope of the barometric gradient, therefore, if the trace is concave we may infer that the wind is likely to decrease in strength, and if convex to increase in strength. It should be remembered that, although a rapid rate of fall, in a general way, indicates worse weather than a moderate one, the inferences drawn from a trace depend on the variation of the rate and not on the rate itself.

If no barograph is available very fair results can be obtained by plotting the hourly readings of the barometer on squared paper, and drawing a curve through the points thus plotted, but of course the minor fluctuations of the barometer do not appear.

On board a ship a difficulty may arise as to what time the barograph should be set to, for obviously the instrument cannot be adjusted in the same manner as the ship's clocks without breaking the continuity of the trace; for this reason it is customary to set the barograph to some standard time, and to note, by a mark, noon S.M.T. of each day, as shown in the Figure.

CHAPTER XXI.

OCEAN CURRENTS, WAVES, &c.

212. Currents.—Having briefly explained the motion of the atmosphere and how to forecast the weather, we have now to give a corresponding explanation with regard to the ocean. The great disturbing influence in the case of the atmosphere is the sun; as regards the ocean, the sun affects it indirectly by first causing the winds, which by friction produce surface movements of the ocean called currents, and, in addition, the sun and moon directly produce a special kind of movement known as the tides, which will be dealt with in Chapters XXII. and XXIII.

As the wind blows over the ocean the surface of the water is dragged onwards and, if the wind continues to blow in the same direction for a considerable time, internal friction causes this onward movement to extend to a considerable depth; such a movement of the ocean, caused solely by the wind, is called a drift current. In Fig. 165 the various currents of the earth are shown, and we find by comparing this figure with Figs. 151 and 152 that the directions of the main drift currents correspond very closely with the directions of the permanent and periodic winds, the Trades, Westerlies, and Monsoons; the currents which correspond to the Trades are called the N.E. and S.E. Trade drifts, those corresponding to the Westerlies are called the Easterly drift currents, and those corresponding to the Monsoons the N.E. and S.W. Monsoon drifts.

When a drift current comes in contact with a shoal, or coast, or with another current, it is deflected, and is then called a stream current; the details of the principal stream currents will now be given, and the reader should bear in mind that the direction of a mass of moving water is not only affected by land which it may approach but, as in the case of the atmosphere, by the Easterly or Westerly movement which it acquires in consequence of the earth's rotation (§ 188).

The sets and drifts of the various currents are shown on the current charts supplied to H.M. Ships and are described in the Sailing Directions.

213. Atlantic Ocean stream currents.

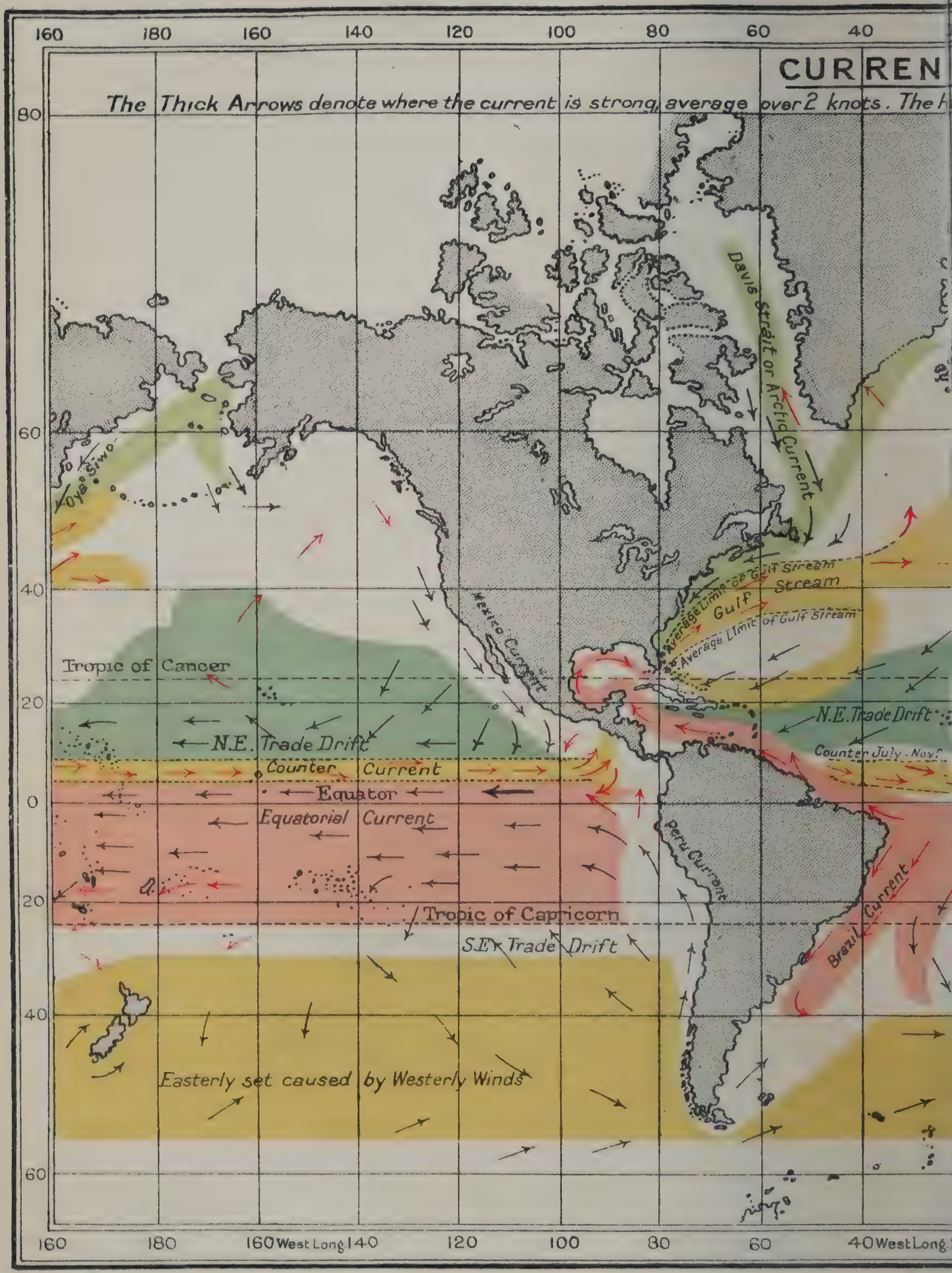
The Equatorial Currents.—The North-East and South-East Trade drifts, on approaching the equator, turn to a Westerly direction and flow across the Atlantic Ocean, nearly as far as the coast of America. The South equatorial current divides at Cape San Roque; each portion follows the coast, one running South forms the Brazil current, and the other running North combines with the North equatorial current and forms the Gulf Stream.

The Gulf Stream.—The portion of the South equatorial current combined with the North equatorial current consists of relatively warm water, and flows North along the coast of South America, passing through the West Indies and the Caribbean Sea; it then flows round the Gulf of Mexico and finds an outlet through the Straits of Florida, which, being narrow and shallow, causes the velocity of the stream to increase. On leaving the Straits the stream consists of relatively warm and salt water, and is 50 miles wide, 350 fathoms deep, with a speed of about 5 knots. From the Straits of Florida it sweeps Northward growing broader and shallower, until at Bermuda it is about 250 miles wide. At about midway across the Atlantic the stream divides; one portion flows towards the British Islands and the other strikes the coast of Europe about the Bay of Biscay, whence it flows along the coast of Portugal into the Mediterranean Sea and causes an Easterly current on the North coast of Africa. A portion of the latter current occasionally curves Northward through the Bay of Biscay and causes a North-Westerly current across the entrance to the English Channel, called the Rennel current.

The area in the North Atlantic Ocean, which is enclosed by the Gulf Stream and the North-East Trade drift, corresponds very closely to the normal high pressure area. Enormous quantities of weed, called Sargasso or Gulf weed, collect in this area which is about 1,000 miles in diameter and is known as the Sargasso Sea.

The Brazil Current.—The portion of the South equatorial current, which turns South along the coast of Brazil, flows as far as the Rio de la Plata, where, on account of the earth's rotation (in accordance with § 188) and assisted by the Easterly motion of the river water, it turns Eastward to mingle with the general Easterly drift of the Southern ocean.

The Davis Strait, Labrador, or Arctic Current.—This current, produced by the prevailing Northerly winds, flows Southward from Davis Strait; it is a cold current and its volume is considerably augmented in summer by the melting of ice. The current hugs the coast of North America passing along the North side of the Gulf Stream, and sometimes flows as far South as Florida. The demarcation between this cold current and the warm Gulf Stream is called the cold wall, and this can be easily detected by the difference in the colours of the water; the Davis Strait current being largely composed of fresh water from melted ice is green, while the Gulf Stream being very salt is a deep blue. In calm weather the cold wall may often



38739 405 W.B.&L.12/1/15

Fig

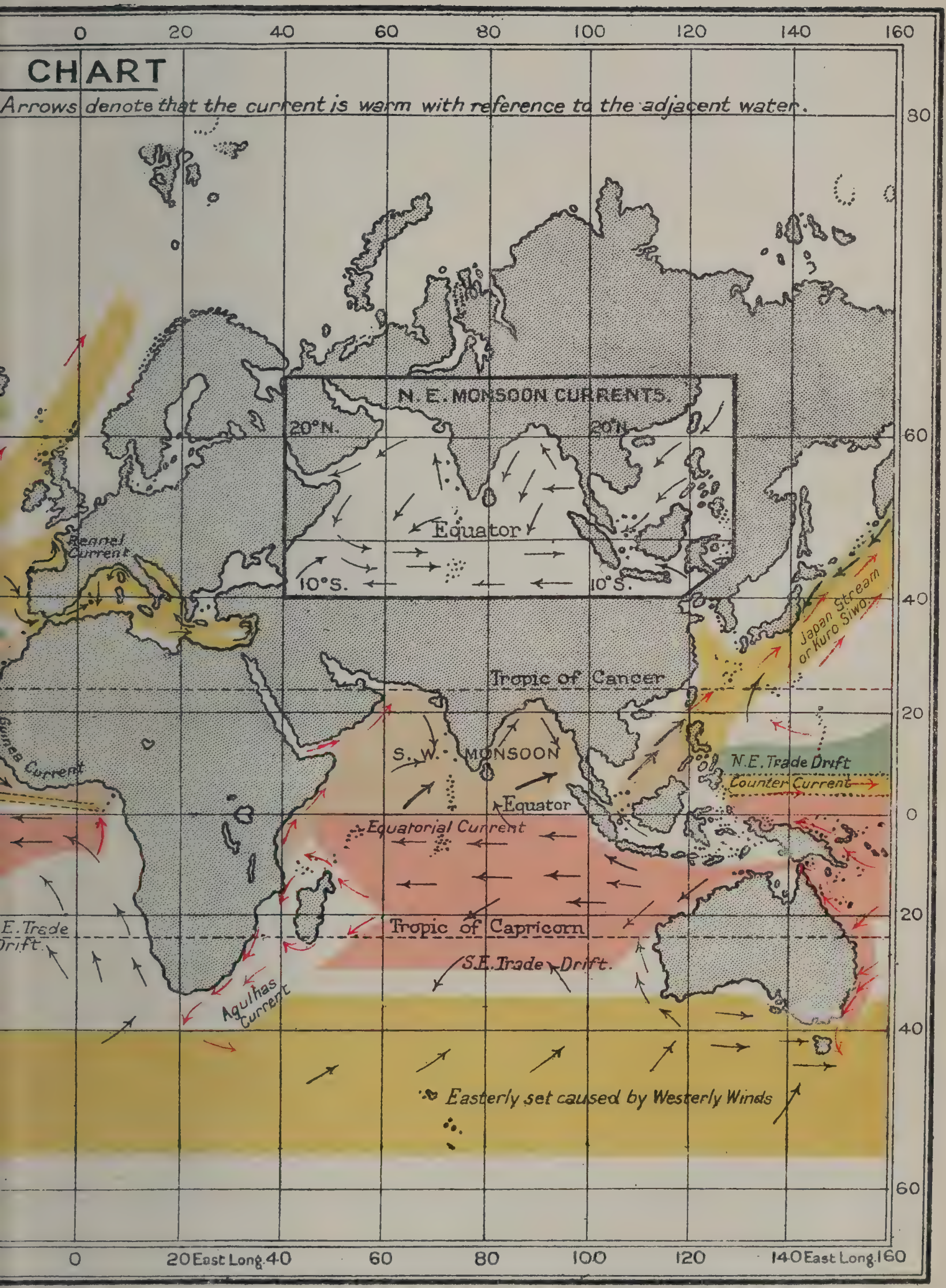


CHART
Arrows denote that the current is warm with reference to the adjacent water.
0
20
40
60
80
100
120
140
160
80
60
40
20
0
20
40
60
N. E. MONSOON CURRENTS.
20°N.
20°N.
Equator
10°S.
10°S.
Rennel Current
Guinea Current
Tropic of Cancer
S. W. MONSOON
Equator
Equatorial Current
Tropic of Capricorn
S.E. Trade Drift.
E. Trade Drift.
Agulhas Current
Japan Stream or Kuro Siwo.
N.E. Trade Drift
Counter Current
Easterly set caused by Westerly Winds
20 East Long. 40
140 East Long. 160

be detected by a ripple; the difference in the temperatures of the surface water, which may sometimes be as much as 30°, also indicates the demarcation between the two streams.

The meeting of these hot and cold streams is the cause of frequent fogs off the banks of Newfoundland. (§ 195.)

The Guinea Current.—The Guinea current, caused by the general oceanic circulation in the North Atlantic, flows along the West coast of Africa as far as latitude 3° N. and has a maximum velocity of 3 knots.

The Equatorial Counter Current.—As the amount of water in the ocean is invariable, and as there is a large volume of water continually moving from the equatorial regions to higher latitudes, it is supposed that a sub-surface current from the higher latitudes rises to the surface between the North and South equatorial currents, and flows Eastward, combining with the Guinea current off the coast of Africa. This current is called the equatorial counter current and runs between the months of July and December.

214. Pacific Ocean stream currents.—In Fig. 165 it will be seen that the currents of the Pacific Ocean differ very little from those of the Atlantic, the principal difference being the periodical change of direction of the drift current in the China Sea due to the change of direction of the Monsoons. The drift currents of the China Sea are called the N.E. and S.W. Monsoon drifts respectively, and correspond in strength to the winds which cause them. Fig. 165 shows the directions of the currents during the S.W. Monsoon, the directions during the N.E. Monsoon being shown in the inset.

The Equatorial Currents.—The South equatorial current, caused, like that of the Atlantic Ocean, by the S.E. Trade drift, flows to the Westward, and on reaching the numerous islands situated between 160° and 170° E. divides into two parts; one runs to the South-West towards Australia where it skirts the coast until it meets the general Easterly drift of the Southern ocean, and the other passes among the islands North of Australia. The North equatorial current flows Westward until it meets the Philippine Islands, where it curves to the North and North-East and becomes the Japan stream.

The Japan Stream.—The Japan stream, often called the Kuro Siwo (Black Stream) on account of its black appearance, is a warm stream, and corresponds to the Gulf Stream in the Atlantic, but is less clearly defined on account of the numerous islands which it encounters. The stream flows along the East coasts of the Philippine Islands, China, and Japan, after which it curves to the Eastward and follows the general Easterly drift of the North Pacific. When off Formosa the stream is about 200 miles wide and has a maximum speed of about 4 knots.

The Oya Siwo.—This is a cold current of pale green water which flows from the Bering Sea to the Southward of the Kuril Islands, and then between the coast of Japan and the Kuro Siwo. Here again the meeting of the hot and cold streams is a cause of frequent fogs.

The Mexican Current.—This is a cold current which corresponds to the Guinea current in the Atlantic and is caused in a similar way.

The Peruvian Current.—This flows in a Northerly direction along the West coast of South America and is due to the general Westerly set being deflected by land.

215. Indian Ocean stream currents.—The currents in this ocean greatly depend on the Monsoons, and in the Northern part chiefly consist of N.E. and S.W. Monsoon drifts.

The Equatorial Current.—This current caused by the South-East Trade drift flows to the West and strikes the African coast about Cape Delgado, where it divides; the part which runs to the North follows the coast of Africa, and during the South-West Monsoon combines with the South-West Monsoon drift; the part which flows to the South forms the Agulhas current.

The Agulhas Current.—The Agulhas current is a warm current; it passes through the Mozambique channel and runs Southward along the East coast of Africa until it is deflected by the Agulhas bank, when it curves to the Eastward and mingles with the general Easterly drift of the Southern ocean. It is a strong current and sometimes attains a speed of 4½ knots.

The Equatorial Counter Current.—This current, which is that portion of the equatorial current which is deflected to the East on meeting the North-East Monsoon drift, runs during the North-East Monsoon.

216. Ocean waves.—Ocean waves are due to the wind blowing obliquely on the surface of the water. When first formed they are short and steep, but if the wind continues to blow in the same direction for a considerable time, their length, that is the distance between successive crests, increases, as also does their height, which is the vertical measurement between their crests and troughs; at the same time the period of the waves, which is the interval between the passages of two successive wave crests over the same spot, decreases, until a time arrives when a balance of forces is reached. When waves have once been formed the wind has its greatest effect on their crests which it tends to drive faster than the main body of the waves, and so causes the waves to break. In deep water, waves have no motion of translation, but on approaching shallow water their troughs are retarded, with the result that they break and rush forward with considerable violence; such waves breaking in shallow water are called breakers.

The dimensions of waves vary in different localities, and with different velocities and directions of the wind. The longest wave recorded is one of 2,600 feet length and 23 seconds period. The longest waves are encountered in the South Pacific, where their lengths vary from 600 to 1,000 feet, and their periods from 11 to 14 seconds. Waves of from 500 to 600 feet in length are occasionally met with in the Atlantic, but more commonly the lengths are from 160 to 320 feet and the periods from 6 to 8 seconds. The relation between the length of a wave and the velocity and direction of the wind is not yet fully understood.

217. To find the dimensions and period of a wave.—Let O_1 and O_2 (Fig. 166) be two observers on the weather side of a ship, their distance apart being l feet. Let AB be a wave crest at the instant of passing O_1, and A_1B_1 the same wave crest at the instant of passing O_2, and let the interval occupied in passing from O_1 to O_2 be t. Let CD be the position of the same wave crest when the next following crest arrives at O_1, and let the interval occupied in passing from O_1 to the position CD be t_1.

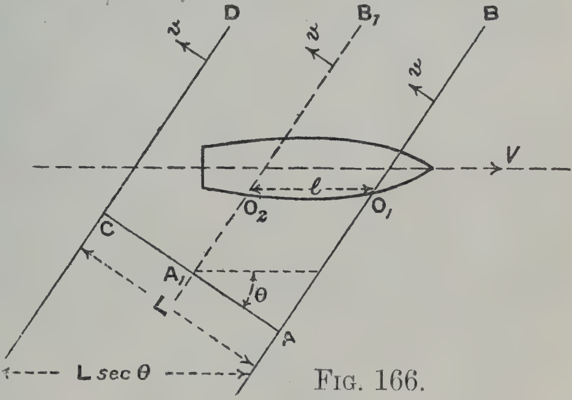


FIG. 166.

Let the length of the wave be L, and the observed angle between the fore-and-aft line of the ship and the direction in which the waves are advancing be θ.

Since the crest passes over the distance $L \sec \theta$ in time t_1 at the same rate as it passes over the distance l in time t, we have

$$\frac{L \sec \theta}{t_1} = \frac{l}{t}$$

$$\therefore\ L = \frac{l t_1 \cos \theta}{t}.$$

Again, let V and v be the speeds of the ship and wave respectively, and let T be the period of the waves.

The velocity of the wave relative to the ship in the direction of the fore-and-aft line is $V + v \sec \theta$, and this is equal to $\frac{l}{t}$.

Therefore $$v = \left(\frac{l}{t} - V\right) \cos \theta.$$

$$\therefore T = \frac{L}{v} = \frac{\dfrac{lt_1 \cos \theta}{t}}{\dfrac{(l - Vt) \cos \theta}{t}}.$$

$$\therefore T = \frac{lt_1}{l - Vt}.$$

The height of a wave is generally found by noting the positions of the trough and crest on the side of the ship.

218. The specific gravity and colour of sea water.—The specific gravity of sea water is found to vary between 1·021 and 1·028, according to its temperature, and to the percentage of salt contained in it.

In the tropics the amount of salt contained in the surface water is above the average, on account of the excessive evaporation which takes place in low latitudes; conversely, in high latitudes the amount of salt is below the average on account of the large amount of fresh water which mixes with it, and which is due to the melting of ice. On the average 77·8 per cent. of the solids contained in sea water consists of common salt; the following is the average percentage of salt which is contained in sea water in different parts of the world:—

Atlantic Ocean - -	3·6
Caribbean Sea - -	3·6
Mediterranean Sea -	3·8
Red Sea - - -	4·1
Indian Ocean - -	3·6

Near large rivers the fresh water running seaward lowers the specific gravity for a considerable distance, for example, the effect of the fresh water of the Rio de la Plata has been detected at a distance of 1,000 miles from the mouth of the river.

The specific gravity of sea water is obtained by means of an instrument called a hydrometer, full directions for the use of which will be found in the Barometer Manual.

It has been found that there is a distinct relation between the colour of sea water and the percentage of salt contained in it; the more salt that is held in solution the more intensely blue the colour, and the less salt the more green is its colour. In landlocked seas such as the Mediterranean and Red Seas where there is little circulation of the water with that of the neighbouring oceans, and where the evaporation is great, the colour of the water is very blue; this is also the colour of the surface water of currents which come from the tropical regions such as the Gulf Stream. The currents which come from polar regions, such as the Davis Strait current, are distinctly green in colour.

Off the estuaries of large rivers the sea water is often discoloured for a great distance by the sediment brought down by the river.

219. Change of draught on passing from sea to river water.—The difference between the specific gravities of sea and river water is of considerable importance in navigation, particularly when a ship has to proceed to a dock which opens into a river, because the draught of the ship varies inversely as the specific gravity of the water in which she floats. The weight of a cubic foot of river water may be taken as 63 lbs. and of sea water as 64 lbs. The increase of the mean draught of a ship when passing from sea to river water is found as follows:—

Let W be the weight of the ship in tons (displacement tonnage), then the volume of water displaced when she floats in river water is $\frac{W \times 2240}{63}$ cubic feet, and when she floats in sea water the volume displaced is $\frac{W \times 2240}{64}$ cubic feet. Therefore, if A is the waterplane area in square feet, the increase of draught is $\frac{2240\ W}{A}\left(\frac{1}{63} - \frac{1}{64}\right) \times 12$ inches, or $\frac{20\ W}{3\ A}$ inches.

Now let T be the number of tons required to sink the ship 1 inch when floating in sea water (tons per inch immersion), then

$$T \times 2240 = \frac{64\ A}{12}.$$

$$\therefore A = 420\ T.$$

Therefore the increase of draught is $\frac{20\ W}{3 \times 420\ T}$ or $\frac{W}{63\ T}$ inches.

Example.—Let us suppose that H.M.S. "Agamemnon" (16,500 tons displacement and 61 tons per inch immersion) is proceeding from sea to Chatham dockyard, then her increase of draught on arrival at Chatham will be $\frac{16500}{63 \times 61}$ inches, or about 4½ inches.

220. Temperature of the sea.—The surface temperature of the sea varies considerably in different parts of the world, and chiefly depends on the temperature of the prevailing currents. Owing to the low conductivity of water a warm current communicates very little of its heat to the water through which it passes.

The temperature of the sea varies throughout the year but the diurnal variation is very small, the temperature being practically the same by night as by day.

In the tropics the average temperature of the sea is about 80° F., the highest readings of about 90°F. being found in the Red Sea. The lowest temperature of the sea is found in the polar regions. The temperature at which sea water freezes is about 28°F.

The normal temperatures of the various oceans are shown on charts supplied to H.M. Ships, where all points, at which the temperatures are the same, are joined by lines called isotherms.

221. Ice.—The sea is completely frozen during the winter months in high latitudes, except where its temperature is raised by warm currents. The Atlantic coast of North America is fringed by ice to a latitude considerably South of that of the English Channel, whereas on the West coast of Europe the Gulf Stream prevents the water from being frozen.

In the spring and summer the ice fields of the polar regions are to a great extent broken up by the winds and tides; the pieces of ice become pressed and frozen together, and the large masses thus formed, called ice floes, are carried by currents into lower latitudes.

Icebergs, which are generally masses of frozen and compressed snow detached from glaciers, are also carried into lower latitudes and, with the icefloes, constitute a serious danger to navigation. In the Atlantic Ocean, icefloes and icebergs have been carried by the Davis Strait current as far South as latitude 39°N.

The majority of the Antarctic icebergs consist of portions broken away from the ice barrier. These are of tabular form, and much larger than those of Greenland. In either the Arctic or Antarctic oceans an iceberg rising to 300 feet above sea level is rare, although bergs of 1,000 feet in height and 20 miles in diameter have occasionally been observed.

Icebergs can seldom be submerged to less than $\frac{7}{8}$ths of their whole volume, so that an iceberg 300 feet high probably draws about 350 fathoms of water, and we conclude that the reason for the absence of icebergs, in the North Pacific Ocean, is probably the comparative shallowness of the Bering Sea.

The proximity of ice is indicated by the following signs, and, should any of them be observed, caution should be used:—

Both by day and night the ice blink is almost always visible on the sky towards the ice. Ice blink is a bright yellowish white light near the horizon, reflected from the snow-covered ice, and seen before the ice itself is visible.

The absence of a swell or motion in a fresh breeze is a sign that there is land or ice on the weather side.

The temperature of the air may fall as ice is approached if the ice be to windward, but not otherwise, and only at an inconsiderable distance from it.

The appearance of herds of seal or flocks of birds far from land is another sign of ice.

The ice cracking, or pieces of it falling into the sea, makes a noise like breakers or a distant discharge of guns, which may often be heard from a short distance.

Recent experiments have shown that the temperature of the sea sometimes rises and sometimes falls in the vicinity of ice; it is therefore unsafe to assume that the proximity of ice will be indicated by a change in the temperature of the sea.

Icebergs and icefloes should not be passed at a close distance owing to the possibility of there being projecting ledges below water; they should, if possible, be passed to windward owing to the possibility of there being smaller masses of invisible drift ice to leeward of them.

The average limits within which ice may be expected are shown on the Pilot Charts and Ice Charts, and are also given in the Sailing Directions.

As the limits of the area, in which ice is liable to be met with, vary at different times of the year, the best tracks to follow when crossing the North Atlantic, between January and August, and between August and January, are given in the Sailing Directions for Westward and for Eastward bound ships.

Occasionally the ice extends over a larger area than usual, and when this occurs the tracks are temporarily modified, notice of such alteration being given in the Notices to Mariners.

CHAPTER XXII.

THEORETICAL TIDES.

222. The tide generating forces.—The movements of the water of the ocean, called currents, which have been considered in the previous chapter, are horizontal; in addition to them there is a rhythmical rising and falling of the water caused by the attraction of the sun and moon—called tides. Several theories have been advanced to account for the tides, no one of which entirely explains the actual movement of the water. The theory which most closely agrees with observation is that known as the equilibrium theory, a brief account of which will be given in this chapter.

We have first to specify the causes by which the tides are generated. In order to simplify the explanation we shall first consider the tide generating force due to the moon alone, and for this purpose we shall commence by supposing that the earth and moon are the only bodies in existence, that the moon is over the earth's equator, and that the earth has no rotation about its axis. On this supposition the earth and the moon revolve in circular orbits about their common centre of gravity *G* (Fig. 167), distant 3,000 miles from the earth's centre, the centripetal force on either body being supplied by universal gravitation.

Since the earth is supposed to be deprived of rotation about its axis it always faces in the same direction in space; therefore its centre describes a circle of 3,000 miles radius about *G*, and any particular face of it is always in the same direction in space.

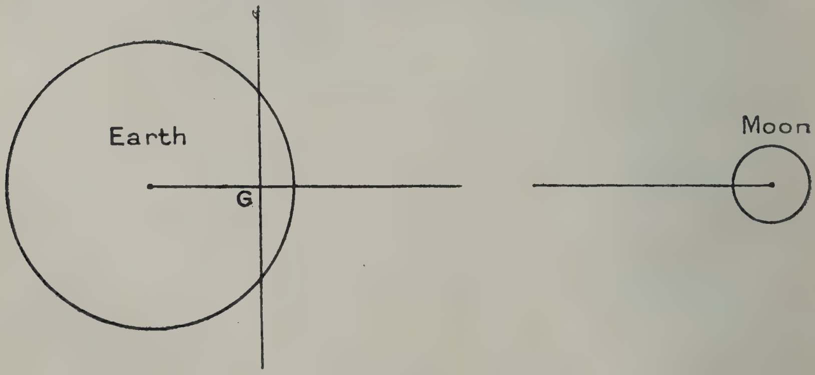


FIG. 167.

In Fig. 168 let C_1 and M_1 be the centres of the earth and moon respectively at a particular instant, and let A_1 and B_1 be the extremities of any diameter of the earth; then, when the moon has moved from M_1 to M_2, C_1 will have moved to C_2 and $A_1 B_1$ to $A_2 B_2$, and it will be seen that every point on the diameter $A_1 B_1$ will have turned on a circle whose centre is on a parallel line through G and whose radius is 3,000 miles. It follows that, at any instant, the centripetal forces on all the particles situated on the line $A_1 B_1$ are equal, and their directions are parallel to the line joining the centres of the earth and moon, as shown by the equal and parallel arrows in the figure. Therefore the centripetal forces at any instant on every particle of the earth are equal, and their directions are parallel to the line joining the centres of the earth and moon at that instant.

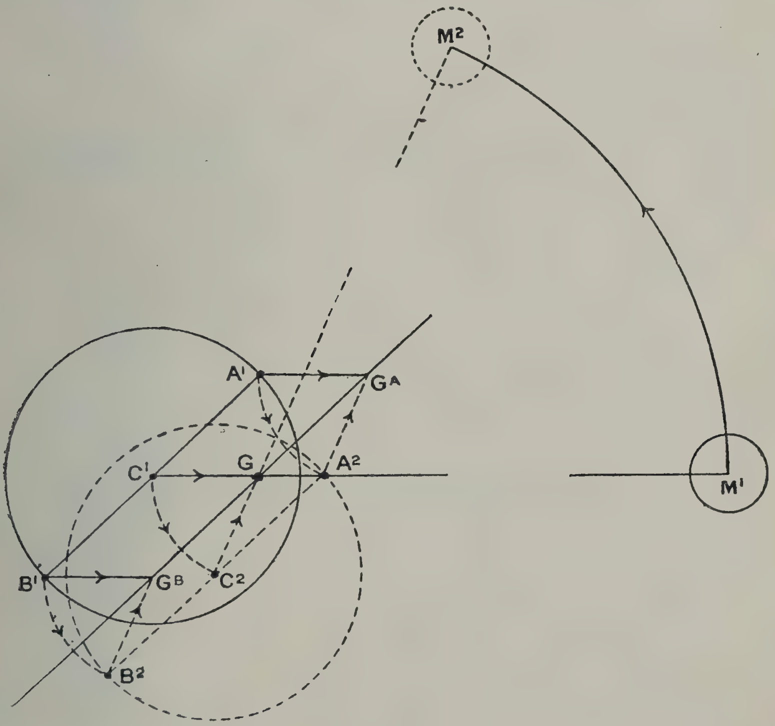


Fig. 168.

Now the centripetal forces on the various particles of the earth are supplied by the attraction of the moon, and the moon attracts every particle of the earth towards itself with a force which varies inversely as the square of the distance. In Fig. 169 the arrows represent the magnitudes and directions of the attractions of the moon on the various particles of the earth. In Fig. 170 the arrows represent the centripetal forces on the same particles, and these forces as explained above are all equal and parallel. Now the attractions have to provide the centripetal forces, so that if we subtract the forces shown in Fig. 170 from the corresponding forces shown in Fig. 169, we shall have a system of residual forces as shown in Fig. 171; these forces are the tide generating forces due to the moon.

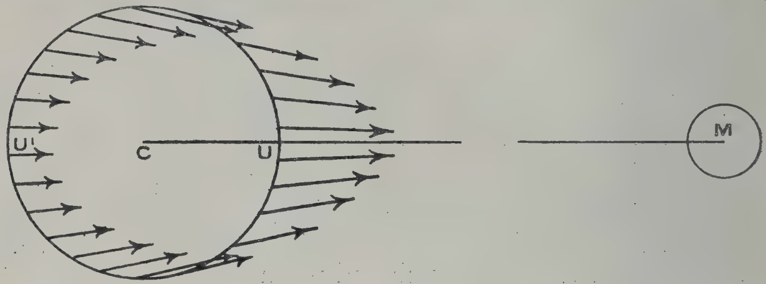


FIG. 169.

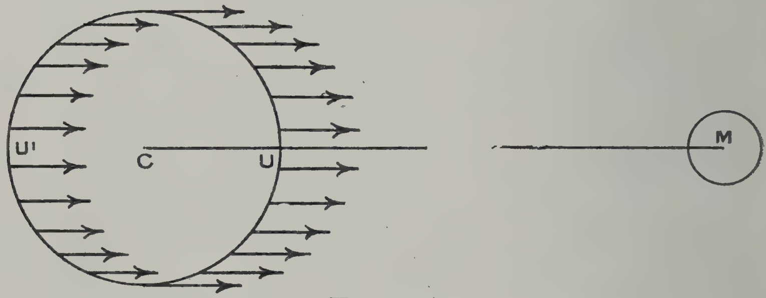


FIG. 170.

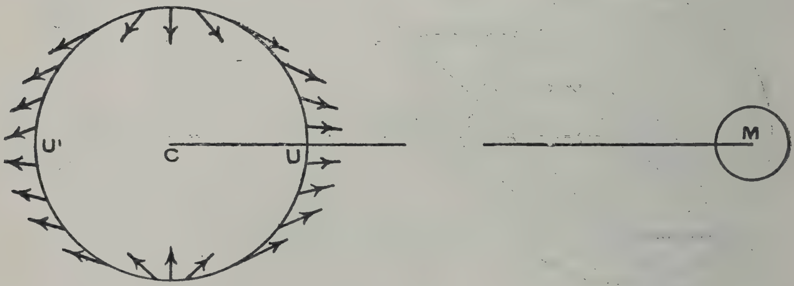


FIG. 171.

Let R be the earth's radius and D the distance CM (Fig. 169) so that the attraction at C is $\frac{k}{D^2}$ where k is the constant of gravitation, then, if U is the geographical position of the moon and U' the point diametrically opposite, the tide generating forces at U and U' are

$$\frac{k}{D^2} - \frac{k}{(D+R)^2} \text{ and } \frac{k}{(D-R)^2} - \frac{k}{D^2}$$

respectively, and if we neglect squares and higher powers of $\frac{R}{D}$, each of these forces is equal to $\frac{2\,k\,R}{D^3}$. Thus the tide generating forces at U and U' are very nearly equal, and the tide generating force at any point whatever may be shown to be inversely proportional to the cube of the distance of the point from the centre of the moon. It can also be shown that the tide generating forces at 54° 44′ from U and U' are tangential to the surface of the earth.

We shall now consider how the tide generating forces tend to affect the ocean.

223. The horizontal tide generating force.—In Fig. 172 let T represent the tide generating force at any point D, and let V and H be its horizontal and vertical components respectively, then the forces acting on a particle at D are gravity $\pm V$ to the centre of the earth, and H horizontally.

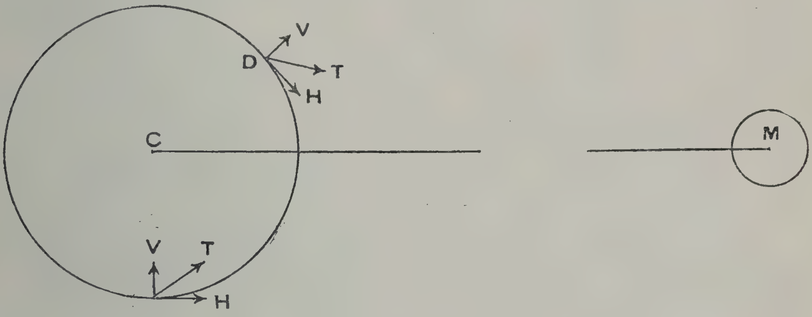


Fig. 172.

Therefore the effect of the tide generating force is to increase or decrease gravity by an insignificant amount, and to leave an unbalanced horizontal force H which is called the horizontal tide generating force.

224. The lunar and anti-lunar tides.—In Fig. 173, the horizontal tide generating forces towards the points U and U' are shown by arrows. If we assume that the earth is entirely surrounded by water of an uniform depth, we see that the water as a whole is subjected to a horizontal pressure towards the points U and U' and away from the meridian QPQ'. The result is that the surface of the water takes an ellipsoidal form

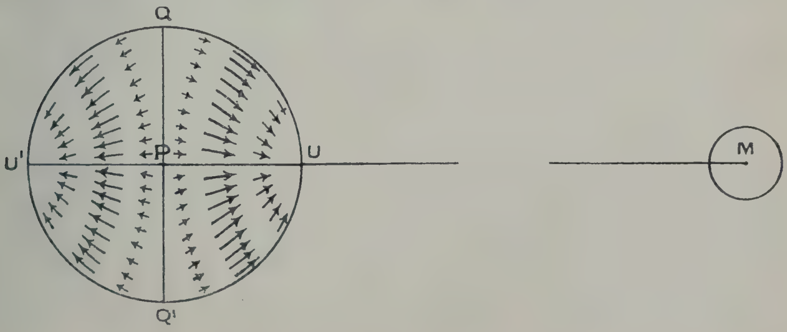


Fig. 173.

as shown in Fig. 174, the level of the water being slightly raised above the mean level over the areas AUB and $A'U'B'$, while over the remainder of the surface of the earth it is slightly depressed below that level. The greatest elevation of the water above the mean level occurs at the points U and U', while the greatest depression occurs along the meridian QPQ'; along the two small circles AB and $A'B'$ the level of the water is unaltered.

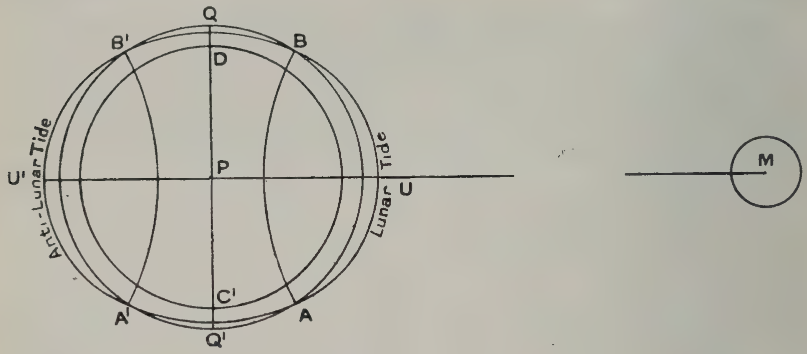


Fig. 174.

If the annular ring of water surrounding the earth at the equator (Fig. 174) be supposed to be cut in two at Q' and unfolded, so that the line which represents the mean level of the sea is a straight line, then the line which represents the level of the sea, when subjected to the tide generating forces, will assume the wave form shown in Fig. 175.

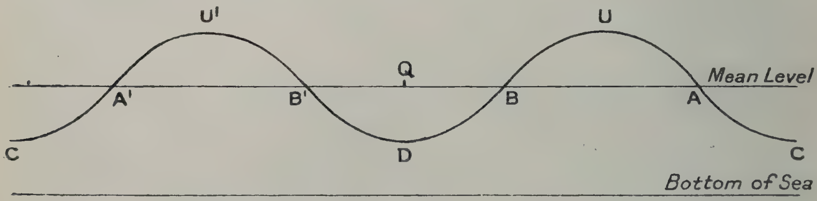


Fig. 175.

The right-hand wave, which corresponds to the elevation of the water immediately under the moon, is called the lunar tide, and the left-hand wave the anti-lunar tide; the points U and U' are the crests of the waves, and the points C and D the troughs.

225. The effect of the earth's rotation.—In Fig. 176, which represents the earth's surface on a Mercator's chart, the crests of the lunar and anti-lunar waves are shown on the prime meridian and the meridian of 180° respectively, the troughs being situated on the meridians of 90° E. and 90° W. At any place on the meridians of 0° and 180° it is said to be high water, and low water on the meridians of 90° E. and 90° W.

Let us now take account of the rotation of the earth on its axis; this will introduce a force which will have no effect on the tide generating force.

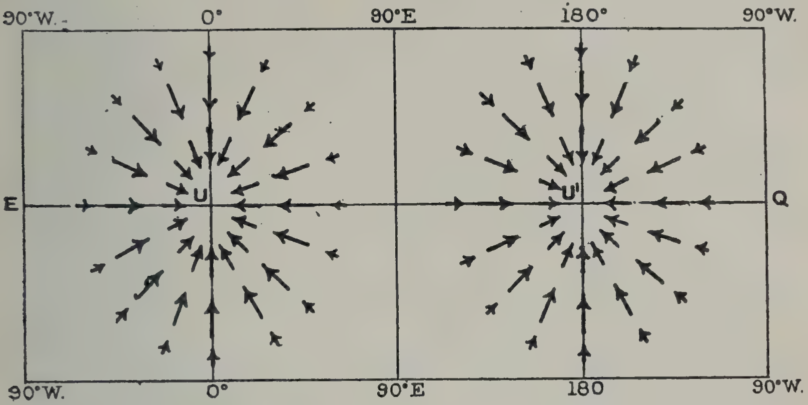


Fig. 176.

As the earth rotates on its axis the points U and U' move over the earth to the Westward and the horizontal tide generating forces move with them, causing high water at successive meridians. It will be seen from the Nautical Almanac that, on the average, the moon crosses the meridian of any place at an interval of $24^h\ 50^m$, and therefore high water occurs on the meridians of 90° E. and 90° W. about 6 hours 12 minutes after it occurred on the prime meridian and that of 180°. Thus, due to the moon alone, high water occurs at any place at the same time as the moon's meridian passage at that place or at the time of the meridian passage of the moon below pole; subsequently the level of the water gradually falls and low water occurs approximately when the moon is setting or rising, after which the level gradually rises again until the next high water. The tide at any place, therefore, alternates between high and low, at intervals of 6 hours 12 minutes approximately.

226. The effect of declination.—So far, we have supposed the moon to be over the equator, and consequently its declination to be zero. Now let us consider the change in the tides at any place due to the declination not being zero.

In Fig. 177, let U be the geographical position of the moon when it has North declination, and let UB be a parallel of latitude, $U'B'$ being the corresponding parallel of South latitude. The crests of the lunar and anti-lunar waves are at U and U', and as the points U, U', B and B' are on opposite meridians the moon causes high water to occur at them simultaneously; but, as the moon's horizontal tide generating force heaps up the water more at U and U' than at any other point, the height of the tide is greater at U and U' than at B and B'. When the earth has turned on its axis through 180° B becomes the geographical position of the moon and B' the opposite point, and it will be seen that the greatest heights of the tide now

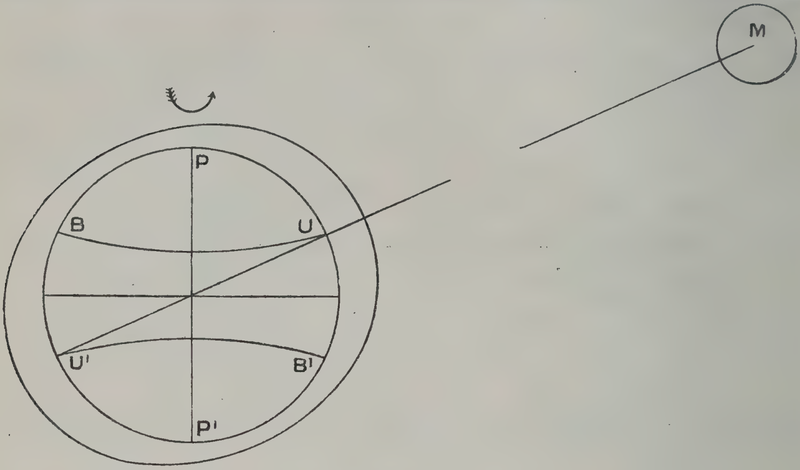


FIG. 177.

occur at B and B'. We conclude that, as the moon's declination has a period of one month, the tides at any place due to the upper meridian passage are higher than those due to the lower meridian passage for a fortnight; during the next fortnight the converse occurs. The difference between the levels of high water of successive tides is called the diurnal inequality of heights.

As the moon moves away from the equator, the tide generating forces experienced at any place deviate more and more from those experienced when the body is over the equator; for this reason a tide produced by the moon, say, the lunar tide, is regarded as the result of two tides; one, the ordinary lunar tide due to the moon being on the equator, and called the lunar semi-diurnal tide because its period is half a lunar day; the other, due to the declination of the moon, is called the lunar diurnal tide because its period is a lunar day.

227. The effect of parallax.—It has hitherto been supposed that the moon revolves at a fixed distance from the earth, but as the moon's actual path round the earth is an ellipse its distance is continually changing; when the moon is nearest the earth it is said to be in perigee and when furthest away in apogee. Now the tide generating forces vary inversely as the cube of the distance, so that they must also vary as the cube of the horizontal parallax. The moon's horizontal parallax has a period of one month, so that for a fortnight the height of the tide exceeds the average and for a fortnight it falls below the average. Taking 57′ as the moon's average horizontal parallax and 61′ as the maximum, the variation from the mean value is $\left(\frac{61}{57}\right)^3 - 1 = \frac{1}{5}$ nearly.

228. The solar and anti-solar tides.—So far the moon has been supposed to exist alone, but the sun acts on the ocean in a similar manner, although, on account of its great distance, with less effect. The mean ratio of the tide generating force of the moon to that of the sun is 7 to 3, so that we conclude that if the sun and earth alone existed there would be tides, similar to those produced by the moon, and of $\frac{3}{7}$ths their height; the interval between high and low water would be 6 hours.

The change in the solar tide at any place due to the sun's declination not being zero is similar to the corresponding change in the lunar tides, and the solar tide may be regarded as a combination of a solar semi-diurnal tide and a solar diurnal tide.

Again, if we consider the change in the distance between the earth and sun due to the earth's orbit being an ellipse, the tide generating forces due to the sun must vary as the cube of the sun's horizontal parallax; as the sun's parallax has a period of one year the height of the solar tide exceeds the average for half a year, and for the next half year it falls below the average. Taking $8''\cdot8$ as the sun's average horizontal parallax and $8''\cdot95$ as the maximum, the variation from the mean value is $\left(\frac{8\cdot95}{8\cdot8}\right)^3 - 1 = \frac{1}{20}$ nearly.

229. The composition of the lunar and solar tides.—So far we have supposed that only one body, the moon or the

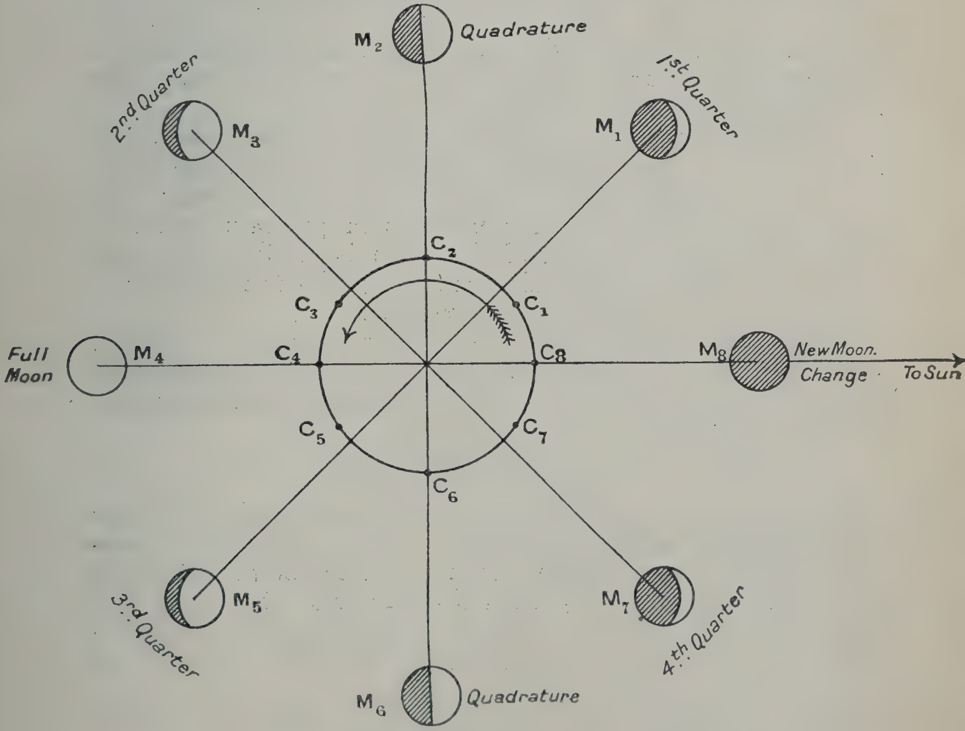


FIG. 178.

sun, is in existence with the earth. Let us now consider the combined effects of the sun and moon assuming their declinations to be zero. The two separate effects, the lunar tide and the solar tide, do not appear separately on the ocean, but there is a single tide which is the resultant, so to speak, of the lunar and solar tides.

Let us suppose that the moon is on the meridian of a particular place at noon, that is at new moon or at change of the moon, M_8 in Fig. 178, then the crests of the lunar and anti-lunar tides are at C_8 and C_4 respectively, and the troughs at C_2 and C_6. Similarly the crests of the solar and anti-solar tides are C_8 and C_4, and the troughs at C_2 and C_6. The result is that the tides, when combined, produce a higher high-water at C_8 and C_4 and a lower low-water at C_2 and C_6. The same result will be seen to occur when the moon is on the meridian at midnight, that is, at full moon, M_4 in Fig. 178. Thus, at full or change of the moon, tides are caused which are about $\frac{3}{7}$ths greater than the lunar or anti-lunar tides, and such tides are called Spring tides from the Saxon *springan* to bulge.

When the moon is in quadrature M_2 or M_6 (Fig. 178) the crests of the lunar or anti-lunar tides are at C_2 and C_6, while their troughs are at C_8 and C_4; the crests of the solar and anti-solar tides are at C_8 and C_4, and their troughs are at C_2 and C_6. The result is that the crests of the lunar and anti-lunar tides combine with the troughs of the solar and anti-solar tides, and the troughs of the lunar and anti-lunar with the crests of the solar and anti-solar. In this case high water occurs at C_2 and C_6, and low water at C_8 and C_4, the high water being about $\frac{4}{7}$ths the size of the lunar or anti-lunar tide. Such tides are called Neap tides from the Saxon *neafte*, scarcity.

It follows that twice in a lunar month, or a lunation, at the time of full or change of the moon, that is, when the moon crosses the meridian at 12^h or 0^h, spring tides occur; that twice in a lunation, when the moon is in quadrature, that is, when the meridian passage of the moon is at 6^h or 18^h, neap tides occur; that the interval from spring tides to neap tides or from neaps to springs is about seven days.

When the moon is over the equator and at any position between full and change and quadrature, its angular distance from the sun (the difference of R.A's) being θ, it can be shown that the height of the composite tide is

$$\sqrt{L^2 + S^2 + 2LS \cos 2\theta}$$

where L and S are the heights of the lunar and solar tides respectively above the mean level of the sea. From this expression it will be seen that the maximum height of the composite tide is $L + S$ and occurs when $\theta = 12^h$ or 0^h, that is, at full and change of the moon (Spring tides); that the minimum height is $L - S$ and occurs when $\theta = 6^h$ or 18^h, that is, when the moon is in quadrature (Neap tides); at any intermediate position the height of the composite tide is, therefore, greater than the neap tide and less than the spring tide.

When we take into account the changes in the declination of the sun and moon, we see that the composite tide, actually experienced at any place, may be regarded as the combination of four tides, two semi-diurnal and two diurnal.

230. Priming and lagging of the tide.—The crest of the composite tide obviously lies between the crests of the lunar and solar tides and nearer to the former; this fact makes it convenient to refer the time of high water at any place to the time that the lunar or anti-lunar tide would have been experienced, had the sun not been in existence, that is, to the time of the upper or lower meridian passage of the moon. The interval between the time of the moon's meridian passage at a place and the time of the arrival of high water, caused by that passage, varies from day to day, and, as explained above, (§ 229) this interval vanishes at full and change of the moon and at quadrature. When the moon is in the first quarter, M_1 in Fig. 178, we see that as the earth rotates in the direction shown by the arrow, an observer will experience high water on arrival at C_1, whereas the moon will cross his meridian some time later at M_1; this interval is called the priming of the tide. The same thing occurs when the moon is in the third quarter.

When the moon is in the second or fourth quarter, M_3 or M_7, we see that it crosses the meridian of an observer before the occurrence of high water caused by that meridian passage, and in these cases there is said to be a lagging of the tide. Thus, when the moon is in the first or third quarter the tides prime, and in the second and fourth they lag.

The symbols L, S and θ having the same significance as in § 229, it can be shown that the angle x between the crest of the composite tide and that of the lunar tide is given by

$$x = \tfrac{1}{2} \tan^{-1} \left(\frac{S \sin 2\theta}{L + S \cos 2\theta} \right)$$

Therefore the priming or lagging of the tide, on account of the moon's motion, § 225, is $\frac{149x}{144}$, which when plotted for various values of θ gives a curve such as $ABCD$ in Fig. 179, the maximum ordinates occurring when the time of the moon's meridian passage is about 4 or 8 hours.

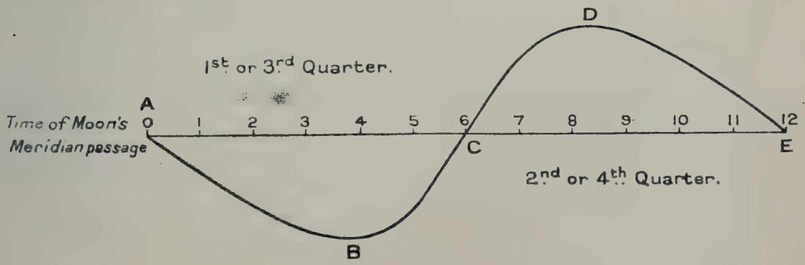


FIG. 179.

As the daily change in the priming and lagging is not great, the interval between two successive arrivals of the same tide crest at any place, sometimes called a tide day, differs very little from the lunar day, the average length of which is $24^h\ 50^m$; consequently high water occurs at any place at intervals of about $12^h\ 25^m$, and the interval between high and low water is about $6^h\ 12^m$.

The theory of the tides which has been briefly sketched above is known as the Equilibrium theory, because it assumes that the tide generating forces have sufficient time to bring the ocean to such a state that all its particles are in equilibrium. Observation appears to indicate that the actual tides of the world conform fairly closely to this theory, but theory only tells us the kinds of phenomena to expect; the amount to be expected, and the time of its arrival at any place, can only be ascertained from the analysis of a large number of observations taken at that place.

CHAPTER XXIII.

OBSERVED TIDES AND USE OF TIDE TABLES. TIDAL STREAMS.

231. Disagreement between theory and observation.—When we reflect on the previous chapter, and remember that the time and place of the tide's crest, on an ideal earth completely surrounded by water, depend on the positions of the sun and moon in right-ascension, on the declinations of the bodies and on their parallaxes, we can see that the theory is extremely complicated; if we take into consideration the large and irregular continents, and the varying depths of the oceans, the theory becomes even more complicated, and we can hardly expect complete agreement between it and observation. Observation agrees fairly closely with the theory; for example, we find that spring tides occur at about Full and Change of the moon, and neap tides at about when the moon is in quadrature; moreover the magnitude of the tide at springs is somewhere about twice that at neaps. The occurrence of maximum and no diurnal inequality corresponds very closely with the moon having maximum declination and no declination respectively, and the magnitude of the tide is found to vary between the times of Perigee and Apogee. In spite of these points of approximate agreement with theory there are a number of points in absolute disagreement, and for this reason the prediction of the tides at any place has to be for the most part based on observation. We shall now explain the meanings of various terms which are made use of in observing the tides.

232. Rise and range of a tide.—To measure any particular tide a datum must be selected from the level of which measurements can be made. In order that the Admiralty charts may show the least depth of water under ordinary conditions, the level selected is generally that of the mean low water of spring tides, so that, if at any place the height of the tide above this level can be calculated for any particular time, it has only to be added to the depth of water at that place, as shown on the chart, to give the depth at that time.

The greatest height to which any particular tide rises above the level of the datum is called the rise of that tide, and its height at any other time (whether the tide is rising or falling) is the height of the level of the water at that time above that of the datum. The rising and falling of the tide are often called the flood and ebb respectively, and the condition of the tide at any time is sometimes expressed in the form, half flood, quarter ebb, &c., by which is meant that the time is half-way between the times of low and high water, or a quarter of the way from the time of high towards the time of low water respectively.

The mean level of the sea at any place is the average level of the sea obtained from a very long series of observations. The mean tide level is the mean between the levels of high and low water obtained from a very long series of observations, and differs very little from the mean level of the sea.

The mean tide level of any tide is the mean between the levels of high and low water of that tide, and may differ very considerably from the mean level of the sea and from the mean tide level.

The range of a tide is the difference between the heights of high and low water of that tide.

A particular tide wave may be represented by a curve such as that shown in Fig. 180, *A* being the crest and *B* the trough, and the figure shows graphically the meanings of the terms —rise and range of tide and mean tide level, for a particular tide.

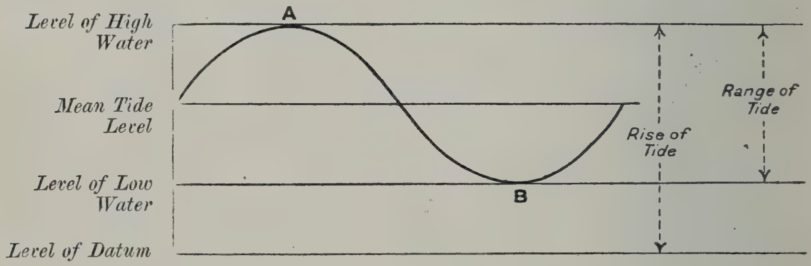


Fig. 180.

The ratio of the rise of the tide at neaps (neap rise) to that at springs (spring rise) is by no means the same for every port, but generally neap rise is $\frac{3}{5}$ to $\frac{4}{5}$ spring rise and neap range $\frac{2}{5}$ spring range. In the tide tables the spring rise is given for nearly all ports, and neap rise is given for a large number. Fig. 181 shows graphically the meanings of the terms neap range, neap rise, spring range, and spring rise; it will be seen that half the spring rise gives the approximate height of the mean level of the sea above the level of datum (§ 246).

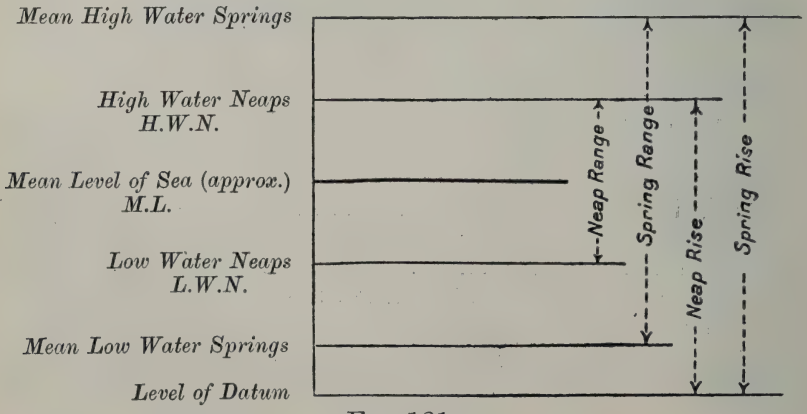


Fig. 181.

From the formula in § 229 we see that the height of any tide depends on the relative positions of the sun and moon in right ascension; in addition to this the height depends on the declinations of the two bodies and on their parallaxes, and consequently the heights of successive spring tides vary. Similarly the heights of successive neap tides vary. When the various causes combine, spring tides occur higher than the mean. When the various causes are in opposition, the spring tides will be lower than the mean. High spring, and low neap, high waters occur at about the equinoxes; low spring, and high neap, high waters at about the solstices. These tides (commonly called "extraordinary spring tides") are called equinoctial and solsticial tides.

The water is not seen to rise to its greatest height and then immediately fall, but it apparently remains at the high level for an appreciable interval; this interval is called the stand of the tide.

The time of high water is the mean between the time at which the water apparently ceases to rise and the time at which it apparently begins to fall; the time of low water is defined in a similar way.

233. The primary and derived tide waves.—Owing to the presence of the land which lies across the path of the theoretical tide crest, it is impossible for such a crest to be formed and to travel round the earth, but in the Southern ocean there is a complete belt of water along which it is possible for the two tide waves to travel; the tide waves which travel round the Southern ocean are called primary waves.

As a primary wave sweeps round the Southern ocean, passing in succession the Southern coasts of Australia, Africa, and South America, it gives off waves which travel freely up the various oceans in a more or less Northerly direction, and which are there unaffected by the sun and moon; these waves are called derived waves, and from them arise the tides along the various coasts which they pass. The primary wave which gives birth to a particular derived wave is sometimes referred to as the mother tide of that derived wave.

If we consider the derived wave which travels up the Atlantic Ocean, we find that it causes high water to occur at the various places which it passes on the West coasts of Africa and Europe; somewhere to the South-west of the British Islands the derived wave sends an offshoot up the English Channel causing high water at the various places on the South coast of England in succession, and a second offshoot up the Irish Channel. The derived wave on passing the North of Scotland sends a third offshoot down the North Sea, and this causes high water at the various places on the East coasts of Scotland and England in succession.

The offshoots which travel up the Irish Sea and the English Channel arrive simultaneously at Liverpool and Dover respectively; the offshoot at Liverpool combines with the main derived wave, while that at Dover combines with the offshoot which has travelled down the North Sea from the previous derived wave.

In the open ocean where the depth is great the height of the derived wave is small and probably less than 3 feet, but on reaching the submarine bank which extends from the British Islands in a South-Westerly direction its height begins to increase, till, on arriving at the coast, it is at some places as much as 25 feet.

Although successive high and low waters on the coasts of the British Islands are caused by the progress of the waves as roughly sketched above, in some cases the tides appear to be caused by two waves; thus, between Portland and Selsea Bill, four tides are experienced in the 24 hours, two of these being probably due to the offshoot which travels Eastward up the English Channel, and the others to a reflected wave moving in the opposite direction. The combination of these two waves has different effects at different places; near the Eastern limit of this length of coast there is a stand of the tide of some duration; in the Solent two distinct high waters occur at an interval of from one to two hours; at Weymouth there is a prolonged or double low water which is locally known as the gulder.

The progress of the derived wave which travels up the Atlantic Ocean cannot be so regularly traced on the coasts of America as on those of Africa and Europe.

The progress of the tide wave may be traced by means of a chart on which all places where the crest of the tide wave arrives at the same time are joined by lines, called co-tidal lines, and such charts are called co-tidal charts. A co-tidal chart for the British Islands and the North Sea will be found in a book (entitled "Tides and tidal streams of the British Islands") which is supplied to H.M. Ships, and which should be studied in connection with this article.

234. The age of the tide.—From the above we see that, in general, a considerable time must elapse, after the birth of a derived wave, before high water is caused at any place by the arrival of that wave; the interval between the times of high water at any place and of that meridian passage of the moon which corresponds to the mother tide is called the age of the tide at that place. The age of the tide is expressed in days to the nearest quarter of a day and may be as much as three days.

The age of the tide is not known for every port of the world. On the West coasts of France, Portugal, and the British Islands the age of the tide is about 1½ days, while in the vicinity of the mouth of the Thames it is 2½ days. At places where little is known about the tides, the age may be estimated from the foregoing, and, in general, at places adjacent to the various oceans it may be assumed to be 1½ days.

The age of the tide may be found from the mean of a large number of observations of the interval between the time of the moon's meridian passage at full or change and the time of the next following highest tide. It should be observed that the age of the tide thus found is the interval between the crest of the mother tide crossing the meridian and the arrival of the derived wave, because, at full or change, the crest of the mother tide is immediately under the moon and there is no priming or lagging (§ 230).

235. The amount of the priming and lagging.—The times represented by the ordinates of the curve for priming and lagging, shown in § 230, depend on the ratio of the height of the lunar tide to that of the solar tide. By taking this ratio as 2·73, the greatest priming or lagging is 44^m, which agrees with observation at London and Liverpool; at Plymouth and Portsmouth observation gives 48^m and 40^m respectively. With 2·73 as the value of the ratio, the priming and lagging for various times of the moon's meridian passage are those given in the following table, which also appears in the Tide Tables under the heading "Correction of Mean Establishment"; the negative and positive values correspond to the priming and lagging of the tide respectively.

Hours of moon's meridian passage.	h. 0	h. 1	h. 2	h. 3	h. 4	h. 5	h. 6	h. 7	h. 8	h. 9	h. 10	h. 11	h. 12
Priming and lagging	m. 0	m. −16	m. −31	m. −41	m. −44	m. −31	m. 0	m. +31	m. +44	m. +41	m. +31	m. +16	m. 0

236. The mean establishment of a port.—The age of the tide roughly refers the time of high water to the time of that meridian passage of the moon which corresponds to the mother tide, and this may be called the meridian passage of the mother moon. Since the age of the tide cannot be found exactly, it is necessary, in order to predict the time of high water on any day, to refer the time of high water to the immediately preceding meridian passage of the moon. The interval between the times of the moon's meridian passage on any day and the next following high water is called the lunitidal interval on that day.

In Fig. 182 let the curve *ABCD* represent the priming and lagging of the primary wave in the Southern ocean, the zero line being *AD*; then the time represented by any ordinate of this curve, when subtracted from, or added to, the time of meridian passage of the mother moon, gives the time of the arrival of the crest of the mother tide on the meridian of any place.

Let *AE* represent the age of the tide (in this case $1\frac{1}{4}$ days) at a particular place; let *EFGH* be the curve *ABCD* transferred parallel to itself through a distance *AE*; then the ordinates of the curve *EFGH*, measured from the zero line *AD*, represent the intervals between the times of the meridian passage of the mother moon and high water at the place; we see that these intervals depend on the amount of priming and lagging of the mother tide.

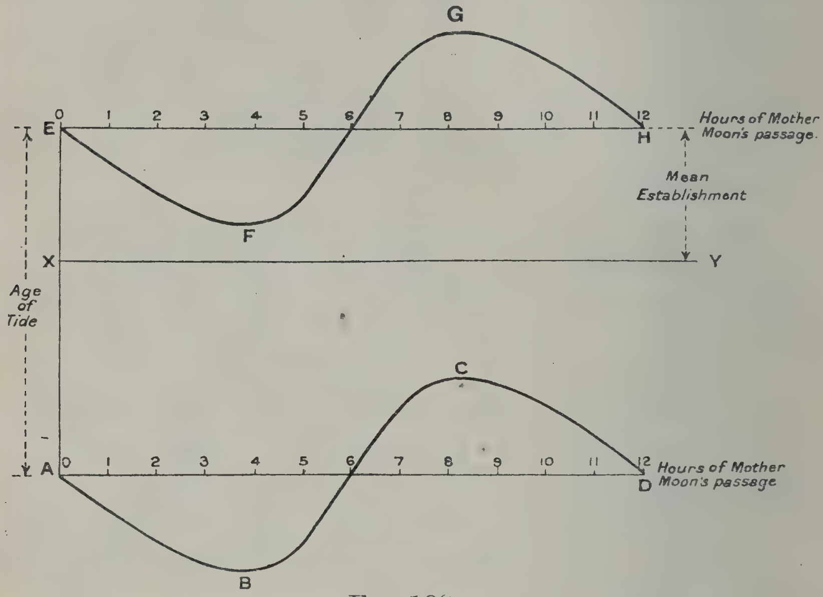


FIG. 182.

The interval represented by *AE* (the age of the tide) consists of a number, or a fractional number, of days, during which the moon may have crossed the meridian of the place several times (in this case twice); it is therefore convenient to measure the ordinates of the curve *EFGH* from a zero line *XY* which is such that the distance *AX* represents a certain number of lunar days. The times represented by the ordinates of the curve *EFGH*, measured from the line *XY*, are the lunitidal intervals, and their mean value during a semi-lunation, represented by *XE* or *YH*, is the mean lunitidal interval at the place or the mean establishment of the port. It will be seen that the lunitidal interval on any particular day differs from the mean lunitidal interval by the corresponding priming and lagging of the mother tide, and that the mean establishment of any place is approximately the time of high water on the day of spring tides because there was no priming or lagging of the mother tide which caused them.

237. To find the time of high water on any day from the mean establishment.—In order to find the time of high water on any day we have to apply the lunitidal interval for that particular high water to the time of the preceding moon's meridian passage. If the mean establishment of the port is known we can find the lunitidal interval by applying to this mean establishment the priming or lagging of the mother tide. To find the latter necessitates the age of the tide being known or assumed.

Example.—It is required to find the time of high water on the afternoon of March 3rd, 1914, at a particular place on the meridian of Greenwich where the mean establishment is $2^h\ 11^m$ and the age of the tide is $1\frac{1}{4}$ days.

From the Nautical Almanac the time of the moon's meridian passage is $4^h\ 44^m$ P.M. Since the moon lags behind the sun 48^m in 24^h, at the birth of the tide, $1\frac{1}{4}$ days earlier, the moon crossed the meridian at which the derived wave was given off $1\frac{1}{4} \times 48^m$ or 1 hour earlier, that is at $3^h\ 44^m$ P.M. Now from the table (§ 235), or from the Tide Tables, we find that for a time of meridian passage $3^h\ 44^m$ the priming of the mother tide was 43^m; therefore the lunitidal interval required is 43^m less than the mean lunitidal interval or mean establishment. The time of high water may now be found as follows:—

Mean establishment	2^h	11^m
Priming of mother tide	—	43
Lunitidal interval	1	28
Time of moon's meridian passage	4	44 P.M.
Time of high water	6	12 P.M.

238. The vulgar establishment of a port, or the H.W.F. & C.—Owing to the difficulty of finding the mean establishment another interval is employed, called the vulgar establishment, which is the lunitidal interval on the days of full or change of the moon. The vulgar establishment is therefore approximately the time of high water on those days, and is shown on the charts in the abbreviated form H.W.F. & C. (high water full and change).

Now the high water on the days of full and change of the moon is due to a mother tide which occurred some days previously, while the moon was still in the second or fourth quarter, when the tides were lagging; therefore this particular lunitidal interval (H.W.F. & C.) is greater than the mean lunitidal interval, in other words, the vulgar establishment of a port, which is the lunitidal interval for a particular tide, is greater than the mean establishment by the lagging of the mother tide at the birth of that tide.

239. To find the time of high water on any day from the H.W.F. & C.—When finding the time of high water, having given the H.W.F. & C., we may proceed as in the previous example, the mean establishment having first been obtained.

Example.—It is required to find the time of high water on the afternoon of March 3rd, 1914, at a particular place on the meridian of Greenwich where the H.W.F. & C. is $2^h\ 27^m$ and the age of the tide is $1\frac{1}{4}$ days.

The H.W.F. & C., being the lunitidal interval on the day of full and change, is greater than the mean establishment by the lagging of the mother tide which took place when the moon's meridian passage was $1\frac{1}{4} \times 48^m$ or 1 hour earlier, that is at 11^h. From the table in § 235 or from the Tide Tables the lagging for a time of moon's meridian passage 11^h is found to be 16^m, so that the mean establishment is $2^h\ 27^m - 16^m$ or $2^h\ 11^m$; the time of high water will now be found to be $6^h\ 12^m$ P.M. as in § 237.

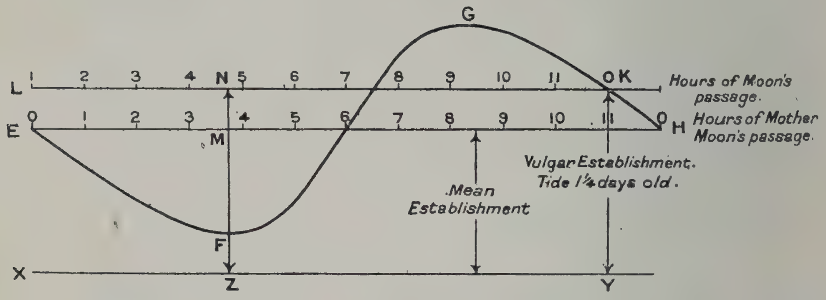


Fig. 183.

In order to simplify the work, the two corrections, namely the lagging of the mother tide on the day of Full and Change, and the priming or lagging of the mother tide at the birth of the tide in question, may be combined as follows.

In Fig. 183 the curve *EFGH* and the lines *EH* and *XY* being the same as those shown in Fig. 182 (§ 236), we have the mean establishment of the port represented by *XE*, and the lunitidal interval for any tide by the ordinate of the curve measured from the base line *XY*, at the point corresponding to the time of the meridian passage of the mother moon.

Let us suppose that the age of the tide is $1\frac{1}{4}$ days, then the H.W.F. & C. is represented by the ordinate *YK*, because the meridian passage of the mother moon, $1\frac{1}{4}$ days before the days of Full or Change, occurred at 11 hours. Through *K* draw a line *KL* parallel to *EH* or *XY*, then, in order to find the lunitidal interval on any day, we have to subtract from the H.W.F. & C., or add to it, the time represented by the ordinate of the curve measured from the line *LK* at that point which corresponds to the time of the meridian passage of the mother moon.

Now, as the meridian passage of the mother moon for any particular tide occurred one hour earlier ($48^m \times 1\frac{1}{4}$) than the meridian passage of the moon on the day in question, it is convenient to graduate the line *LK* so that the divisions represent the hours of the preceding moon's meridian passage, and this is done by moving each graduation one place to the left, that at *K* becoming 0^h, and so on.

In the example just given, where the age of the tide was 1¼ days, the lagging of the mother tide, corresponding to the day of Full and Change, was 16^m represented by *MN*; the priming of the mother tide on the day when the moon crossed the meridian at 4^h 44^m P.M. (the meridian passage of the mother moon being 3^h 44^m P.M.) was 43^m represented by *MF*. The total correction to the H.W.F. & C. is – 59^m represented by the ordinate *NF*. The lunitidal interval is therefore represented by ZF = H.W.F. & C. – FN = 2^h 27^m – 59^m = 1^h 28^m.

In a similar manner a line such as *LK* may be drawn for any other age of the tide.

In the Tide Tables there are two tables which give the times represented by the ordinates of the curve, (1) for a tide 1¼ days old, and (2) for a tide 2½ days old.

The age of the tide is not known for every place, and where it is unknown and cannot be estimated (§ 234), it is customary to assume that it is between 1¼ and 2½ days, and to take the mean of the corrections given in tables (1) and (2) of the Tide Tables.

The H.W.F. & C. is given in the Tide Tables for nearly all ports and anchorages. As it is the approximate time of high water on the days of Full and Change it is given as G.M.T. as well as M.T.P. This is a convenience when the ship's clocks are set to G.M.T. or any standard time (§ 89).

240. Examples of finding the time of high water.—The G.M.T. of the moon's upper meridian passage at Greenwich is given for every day of each month in a table at the beginning of the Tide Tables, immediately before the tide predictions, signifying morning and afternoon. The age of the moon, in days, is also given.

Example (1).—Find the approximate time of high water on the morning of March 19th, 1914, at Port Natal.

The following information is given in the Tide Tables:—

Port Natal. Longitude 31° 04′ E. H.W.F. & C. (M.T.P.) 4^h 30^m. Moon's meridian passage 6^h 31^m.

Moon's mer. pass.	6^h 31^m A.M.	H.W.F. & C.	4^h 30^m
Cor. for Long.	– 5	Mean from tables (1) and (2)	– 51
M.T.P. of moon's mer. pass.	6 26	Lunitidal interval	3 39
Lunitidal interval	3 39		
M.T.P. of high water	10 05 A.M.		

Example (2).—Find the approximate time of high water on the afternoon of March 3rd, 1914, at Richmond Island (U.S.).

The following information is given in the Tide Tables:—Richmond Island. Longitude 70° 14′ W. H.W.F.&C. (M.T.P.) $11^h\ 03^m$. Moon's meridian passage $4^h\ 44^m$ P.M.

Moon's mer. pass.	$4^h\ 44^m$ P.M.	Mar. 3rd.
Cor. for Long. -	+10	
M.T.P. of moon's mer. pass. - -	4 54 P.M.	
Lunitidal interval	9 58	
M.T.P. of high water - - -	2 52 A.M.	Mar. 4th.
Duration of one tide -	12 25	
M.T.P. of high water - -	2 27 P.M.	Mar. 3rd.

H.W. F. & C. - -	$11^h\ 03^m$
Mean from tables (1) and (2) - - -	−1 05
Lunitidal interval -	9 58

If it is required to find the time of low water, $6^h\ 12^m$ should be added to, or subtracted from, the time of high water.

As will be explained in §§ 241, 242, this method of finding the time of high water gives results which are approximate only, and therefore should only be employed when neither of the methods which are explained hereafter are available.

241. Diurnal inequality.—In the preceding article examples of finding the time of high water were given but no account was taken of the effect of declination or, in other words, of diurnal inequality (§ 226). In many parts of the world the diurnal inequality is so great that we cannot find the time of high water from the H.W.F. & C. There is diurnal inequality of the times as well as of the heights of the tides, but no practical rule can be given for calculating the amount of either; therefore, at a place where diurnal inequality is pronounced, it is only possible to predict the tides from an analysis of a large number of observations at that place. The general conclusion as regards diurnal inequality appears to be that the day tides are highest in summer and the night tides highest in winter; diurnal inequality is revealed in the times of high water and in the heights of low water. At some places the diurnal inequality of heights occasionally becomes so great that the difference in heights of high and low water of one of the tides is inappreciable, and in such a case the tide rises for 12 hours and falls for 12 hours; such tides are called single day tides.

The tides of British Columbia, and of the majority of the ports of India, and China, are affected in a marked degree by diurnal inequality.

242. Tide prediction. Standard ports.—Owing to the fact that changes in the time of high water, due to the changes in the declination and parallax of the sun and moon, are not allowed for in the method of finding the time of high water by the H.W.F. & C., it is impossible to accurately predict the time of high water by this method. The spring and neap rise, although known for very many ports, give little guidance for finding the height of the tide at intermediate times because of the changes in the declination and parallax. For the above reasons the tides for a large number of ports of the United Kingdom and other countries — called Standards ports in the Tide Tables—are predicted by one of two methods. The tides for the Standard ports of the United Kingdom and Brest are predicted by the aid of a number of constants which are given in the preface to the Tide Tables, while those of other Standard ports are predicted by aid of a method known as the harmonic analysis of the tides. For certain of the more important Standard ports the times and heights of low water are given in addition to those of high water. At ports where only the times and heights of high water are given the average duration of the rise and fall of tide is given. The height given for any particular tide is the rise of that tide above the level of a particular datum, which, except in a few places enumerated in the preface to the Tide Tables, is that of mean low water springs.

In addition to the Tide Tables published by the Admiralty some of the colonial governments publish tables for their own ports; these tables are supplied to ships which are likely to visit those ports.

243. To find the height of the tide at any time, &c.—Let *D*, Fig. 184, be the level of the datum and *S* the level of the water at an interval *t* hours after high water. Let *A* and *B* be the levels of high and low water respectively, so that *AB* is the range of the tide and its middle point *C* the mean tide level of the tide.

Let *T* be the time occupied by the water in falling from *A* to *B*, that is the interval between the times of high and low water.

The height of the tide, *t* hours after high water, is *DS*, which is equal to $DC \pm CS$.

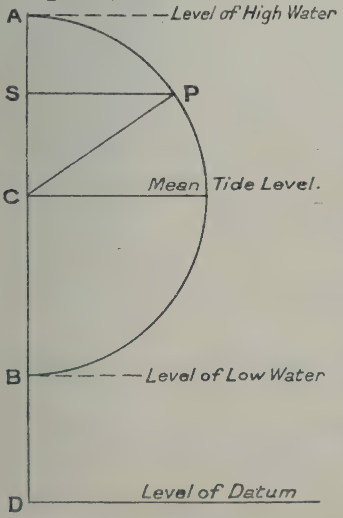


Fig. 184.

DC is the height of the mean tide level and is the mean of the heights of high and low water.

CS is the height of the tide above or below mean tide level. Now the tide may be assumed to rise and fall with simple harmonic motion, so that *S* moves from *A* to *B* in such a way that it is the projection on *AB* of a point *P* which travels uniformly in the semicircle described on the range *AB* as diameter. Therefore the position of the point *P*, *t* hours after high water, is given by

$$\frac{ACP}{180^\circ} = \frac{t}{T}$$

and hence *CS* can be found.

At those places where the height of low water is not given in the Tide Tables, the mean tide level of any tide must be assumed to be the same as that of an ordinary spring tide, and therefore the half range of any tide must be assumed to be the difference between the rise of that tide and half the spring rise.

Conversely, if it is required to find the time after high water at which the tide will be at a given height, the position of the point *P* is found by first plotting the given level of *S*; the angle *ACP* may then be measured, and the time obtained from the relation given above.

The method just described should not be used for places where the tides are known to be irregular, such as in the Solent and where single day tides occur.

244. Examples of finding the height of the tide at any time, &c.:—

Example (1).—On March 9th, 1914, at $11^h\ 30^m$ A.M., Dublin time, it is required to find the height of the tide at Kingstown.

The following information is given in the Tide Tables:—

	M.T.P.†	Height. ft. ins.
Preceding high water -	$9^h\ 06^m$ A.M.	10 03
Succeeding low water -	2 53 P.M.	2 04

	ft. ins.
Height of tide at H.W. - -	10 03 = *DA*
Height of tide at L.W. - -	2 04 = *DB*
	12 07
Height of mean tide level - -	6 03 = *DC*

	ft. ins.
Height of tide at H.W. - -	10 03 = *DA*
Height of tide at L.W. - -	2 04 = *DB*
Range - -	7 11 = *AB*
Half range - -	4 00 = *BC*

Draw a line *DF*, Fig. 185, to represent the level of the datum, and at any point *D* erect a perpendicular *DC* to represent the height of mean tide level on any convenient scale. With centre *C* and radius 4 ft. (on the same scale), describe a semi-circle, cutting *DC* produced in *A* and *B*.

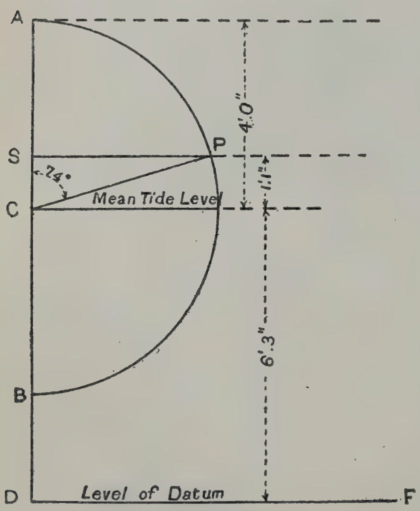


FIG. 185.

M.T.P. of L.W. -	$2^h\ 53^m$ P.M.
M.T.P. of H.W. -	9 06 A.M.
Time tide takes to fall (*T*) - -	5 47
M.T.P. of H.W. -	$9^h\ 06^m$ A.M.
Longitude - -	—1
Dublin time of H.W.	9 05 A.M.
Time at which height is required - -	11 30 A.M.
Interval after H.W. (*t*)	2 25

---

† In the 1915 Tide Tables, the predicted times are usually given for Standard time; *vide* the note at the foot of each page of the predictions.

The angle ACP is, therefore, $180° \times \frac{2\cdot 4}{5\cdot 8} = 74°$.

Lay off the angle $ACP = 74°$, and draw PS perpendicular to AB, then S is the level of the water at the time required.

will be 40 feet, at a position where the depth given on the chart is 4½ fathoms.

The following information is given in the Tide Tables :—

	M.T.P.	Height.
High water	11h 15m A.M.	16 ft. 8 ins.

Tide rises in 5h 40m approximately.
Mean tide level 10 ft. 5 ins.
The level of the datum is that of mean L.W. springs.

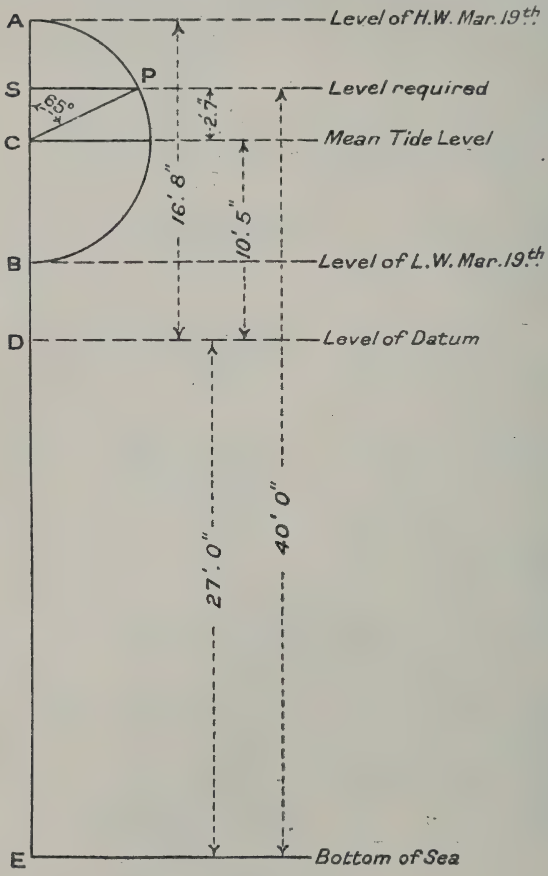


Fig. 187.

	ft.	ins.	
Height of tide at H.W.	16	8	= *DA*
Height of mean tide level	10	5	= *DC*
½ range of tide	6	3	= *CA*
Depth charted	27	0	= *ED*
Height of mean tide level	10	5	= *DC*
Depth of water when at mean tide level	37	5	= *EC*
Depth required	40	0	= *ES*
Height above mean tide level	2	7	= *CS*

Draw the horizontal line PS so that CS represents 2 ft. 7 ins., then the angle ACP will be found to be 65°.

Therefore the depth of the water will be 40 ft. at $\frac{65}{180} \times 5^h\ 40^m$, or $2^h\ 3^m$ before high water.

M.T.P. of H.W. - - - -	$11^h\ 15^m$ A.M.
Long. of Hull - - - -	1 (W.)
G.M.T. of H.W. - - - -	11 16 A.M.
Time before H.W. - - - -	2 03
G.M.T. required - - - -	9 13 A.M.

Example (4).—During daylight on March 13th, 1914, between what G.M.T.s will the depth of water be greater than 28 feet over a 3 fathom bank at Harwich?

The following information is given in the Tide Tables:—

	M.T.P.	Height.
		ft. ins.
Low water - -	$6^h\ 18^m$ A.M.	0 3
High water -	0 35 P.M.	13 4
Low water - -	6 17 P.M.	1 0

Rising tide.	ft.	ins.	Falling tide.	ft.	ins.
Height of H.W. -	13	4	Height of H.W. -	13	4
Height of L.W. -	0	3	Height of L.W. -	1	0
	13	7		14	4
Height of mean tide level - -	6	9	Height of mean tide level - -	7	2
	ft.	ins.		ft.	ins.
Height of H.W. -	13	4	Height of H.W. -	13	4
Height of L. W. -	0	3	Height of L.W. -	1	0
Range - -	13	1	Range - -	12	4
Half range - -	6	7 $= CA$	Half range - -	6	2 $= C'A'$
	ft.	ins.		ft.	ins.
Least depth required	28	0	Least depth required	28	0
Depth charted -	18	0	Depth charted -	18	0
Least height of tide required - -	10	0	Least height of tide required - -	10	0
Mean tide level -	6	9	Mean tide level -	7	2
Least height required above mean tide level - -	3	3 $= CS$	Least height required above mean tide level - -	2	10 $= C'S'$

It will be found that the angles SCP and $S'C'P'$ are 60° and 63° respectively.

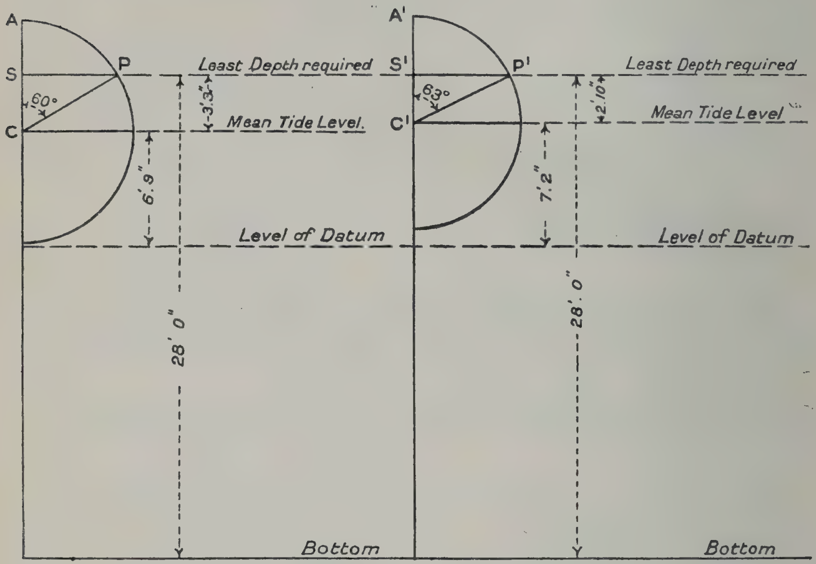


Fig. 188.

Rising tide.		Falling tide.	
M.T.P. of H.W. -	$0^h\ 35^m$ P.M.	M.T.P. of L.W. -	$6^h\ 17^m$ P.M.
M.T.P. of L.W. -	6 18 A.M.	M.T.P. of H.W. -	0 35 P.M.
Time tide takes to rise	6 17 (T)	Time tide takes to fall	5 42 (T')
Interval from H.W. $\frac{60}{180} \times 6 \cdot 3 =$	$2^h\ 6^m$ (t)	Interval from H.W. $\frac{63}{180} \times 5 \cdot 7 =$	$2^h\ 0^m$ (t')
M.T.P. of H. W. -	$0^h\ 35^m$ P.M.	M.T.P. of H.W. -	$0^h\ 35^m$ P.M.
Longitude - -	5 (E)	Longitude - -	5 (E.)
G.M.T. of H.W. -	0 30 P.M.	G.M.T. of H.W. -	0 30 P.M.
Time before H.W. -	2 06	Time after H.W. -	2 00
G.M.T. required -	10 24 A.M.	G.M.T. required -	2 30 P.M.

Therefore the depth of water over the bank will be greater than 28 ft. between $10^h\ 24^m$ A.M. and $2^h\ 30^m$ P.M. G.M.T.

To avoid the necessity of drawing a diagram for every problem, diagrams are given in the Tide Tables in which the radius of the circle is represented as varying from 1 to 11 feet, and the line CP is laid off for every half hour from the time of high water. Diagrams are given for tides which take 5, $5\frac{1}{2}$, 6, $6\frac{1}{2}$, and 7 hours to rise or fall. For a tide which does not rise or fall in an exact number of half hours, the height above mean tide level may be found by interpolating between the results obtained from two diagrams.

245. Comparison between the tides at two places. Tidal constants.—On the days of Full and Change of the moon the difference between the local times of high water at two places is the difference between their Vulgar Establishments, but this is not true on any other day of the lunation unless the age of the tide is the same at both places. For this reason the Mean Establishment, being unaffected by the age of the tide, should be used when comparing the times of high and low water at two places, or when tracing the progress of a tide wave along a coast.

The times and heights of high water, at a certain number of ports, can be found by applying corrections to the times and heights of high water at those standard ports which have the same age of the tide; these corrections are called tidal constants, and are given in the Tide Tables for a large number of ports and anchorages in the United Kingdom and its dominions, as well as for certain foreign ports. To illustrate the use of tidal constants let us consider the following.

Example.—On March 17th, 1914, at what G.M.T. (about midday) will there be 35 feet of water over a 5-fathom bank at Port Patrick?

The following information is given in the Tide Tables:—

Port Patrick - Standard port, Greenock.
Time constant $-\ 0^h\ 58^m$.
Height constants, Springs, + 5 ft.
Neaps, + 3 ft. 9 ins.
Springs rise 15 feet.
Longitude in time, 20^m (W.)

	M.T.P.	Height.
Greenock -	H.W. $3^h\ 34^m$ P.M.	9 ft. 5 ins.

Tide rises in $6^h\ 30^m$ approximately.

March 17th is three days after spring tides.

Mean tide level at Port Patrick is 7 ft. 6 ins. = DC, Fig. 189. The height constants are 5 ft. and 3 ft. 9 ins. at springs and neaps respectively; therefore, since the date is three days after springs, the constant for March 17th is + 4 ft. 6 ins.

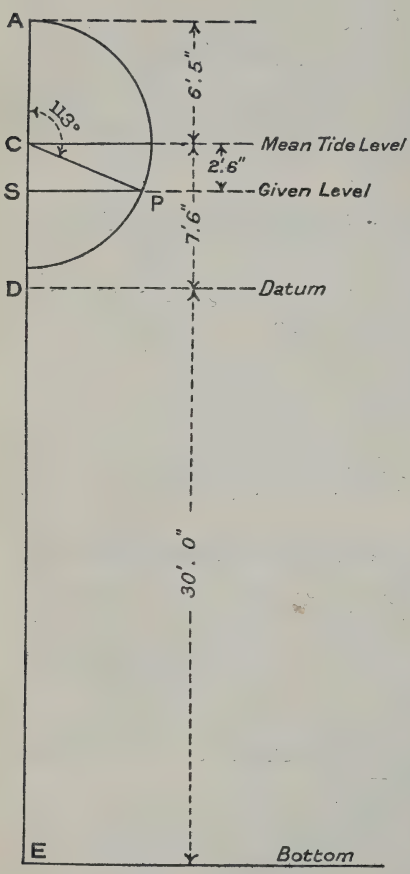


Fig. 189.

	ft.	ins.
Height of H.W. Greenock	9	5
Height constant	+ 4	6
Height of H.W. at Port Patrick	13	11
Mean tide level at Port Patrick	7	6
½ range of tide at Port Patrick	6	5 = *CA*

	ft.	ins.
Depth required	35	0
Depth charted	30	0
Height of tide required	5	0
Mean tide level	7	6
Depth below mean tide level	2	6 = *CS*

The angle *ACP* is found to be 113°, therefore the time before high water is $\frac{113}{180} \times 6\cdot5$ hours = $4^h\ 05^m$

M. T. P. of H. W. Greenock	$3^h\ 34^m$ P.M.
Time constant	— 0 58
M.T.P. of H.W. Port Patrick	2 36 P.M.
Long. of Port Patrick	20 (W.)
G.M.T. of H.W. Port Patrick	2 56 P.M.
Time before H.W.	4 05
G.M.T. required	10 51 A.M.

246. Effect of meteorological conditions.—The mean tide level of any tide is affected by the wind and by changes of atmospheric pressure. The wind produces a considerable effect on the tides and, generally, an onshore wind raises the level of the water while an offshore wind lowers it; for example, at Liverpool, South-Westerly winds raise the level while Easterly winds lower it. In ports with narrow entrances the wind may alter the times of low and high water, for example, at Portsmouth, a Northerly wind may delay the flood as much as three-quarters of an hour.

As regards the effect of change in atmospheric pressure, the mean level of the sea rises or falls as the barometer falls or rises, the change in the level being 1 inch for about $\frac{1}{20}$th of an inch of mercury. The effect of change in atmospheric pressure, as well as the possible effect of wind, should be taken into consideration when great accuracy is required; the mean level of the sea at any place should be assumed to be correct when the barometer is at its average height for that place.

247. The cause of tidal streams.—The direct effect of the sun and moon is to produce the vertical movements of the water which have been discussed above under the name of tides. So long as we consider the tides in the ocean, where the depth is great, there is practically no horizontal movement of the water, the height of the wave being only two or three feet while its length is some hundreds of miles; when, however, a tide wave meets a submarine plateau, its height increases considerably, its length diminishes, and its speed decreases; the consequence of this is that the gradient from crest to trough becomes sufficiently great to allow the water to flow from the higher to the lower level, and such a flow of water is called a tidal stream.

In Fig. 190 let *ABCDE* be a tide wave moving in the direction shown by the arrow, *A* and *E* being crests, and *C* a trough. As the crests and trough pass an observer there is no gradient, while at the points *B* and *D* there is a tendency of the water to move in the directions shown by the small arrows. When the crest of a tide wave approaches an inlet it is preceded by a stream running in the same direction, and when the crest recedes from the inlet it is also preceded by a stream; such tidal streams, when their directions change within an hour of high or low water, are called the flood tidal stream and the ebb tidal stream respectively, and are indicated on the chart as shown in § 160.

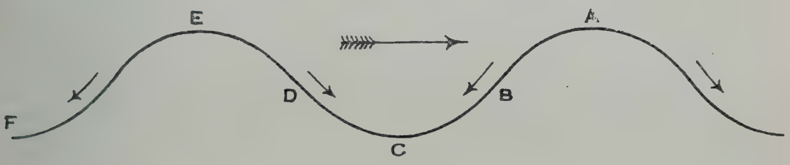


Fig. 190.

When a tidal stream first begins, there is a flow of the surface water only, but as the tide wave arrives in shallower water the horizontal movement extends to a considerable depth, and finally, if the depth is sufficiently small the whole mass is in motion.

248. Tidal streams in a channel.—As the tide wave, Fig. 190, passes an observer, the crest, trough, and intermediate points pass in succession, moving in the direction shown by the large arrow which we will suppose to be East. While the wave form extending from B to C is passing there is a Westerly stream, and this continues to flow, after the trough C has passed, till its momentum has been checked by the gradient between C and E, when an Easterly stream begins to flow. Similarly there is an Easterly stream at E which continues to flow till checked by the gradient between E and F, when the stream is again Westerly.

249. Times of turning of tidal streams.—From the above it will be seen that, in general, the tidal streams at any place will not turn at the times of high and low water at that place. The time of the turn of a tidal stream is generally referred to the time of high or low water of some adjacent port or anchorage, but in some places the time at which a particular stream begins to flow is given on the chart for the days of Full or Change of the moon; for example "North-Easterly stream begins at IX^h F. & C." indicates that on the days when the moon crosses the meridian of the place at 12^h or 0^h, a stream begins to flow to the North-Eastward at 9 o'clock. This is analogous to the use of the vulgar establishment of the port with respect to tides, and the beginning of the stream on any day may, therefore, be found in a similar way to that of finding the time of high water from the H.W.F. & C. (§ 239). In a few places the time of the turn of the tidal stream is referred to the age of the moon.

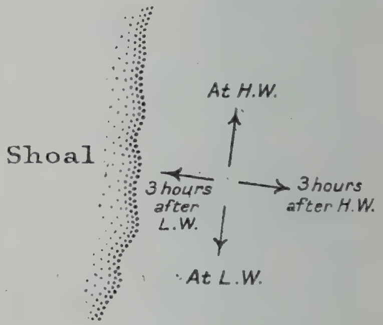


Fig. 191.

The time at which a tidal stream turns is often different at different distances from the shore, being generally rather later in the offing than inshore. In the vicinity of shoals which dry at low water the direction of the tidal stream is affected by the water flowing on and off the shoal, and is different at different stages of the tide; such a stream is called a rotary stream, and is illustrated in Fig. 191.

250. The rates of tidal streams.—As a general rule the rate of a tidal stream at any place varies throughout a lunation, being least and greatest at the times of neap and spring tides respectively. The rates shown on the chart are the average rates at those times; for example, the tidal stream at a certain position in the English Channel is shown on the chart as 233° (S. 67° W. Mag.), average rate, ½ to 1½ knots.

As was explained in § 247, tidal streams are caused by the tide wave meeting a submarine plateau, and, naturally, when it reaches comparatively shoal water, the presence of rocks or irregularities in the bottom bring about local changes in the directions and rates of the tidal streams; thus it is found that the rate of a tidal stream is greater in the close proximity of salient points than in the offing.

Where a submarine ridge of rocks rises abruptly the tidal stream flows over it at a great rate, and the surface of the water is very disturbed; at such a place the tidal stream is called a race, many examples of which are found round the British Islands, the most familiar being that South of Portland Bill.

Where sudden changes of depth occur the tidal stream presents the appearance of a miniature race, and in this case it is called an overfall or tide rip, examples of which may be seen, in settled weather, above the edge of the submarine plateau on which the British Islands are situated.

An eddy is a small local whirl in the water and is found in places where the tidal streams are strong and the bottom very irregular.

Races, overfalls, or tide rips, and eddies are indicated on the charts as shown in § 160.

251. The tidal streams round the British Islands.—The times of turning of the tidal streams round the British Islands and in the North Sea are referred, on the charts, and in the Sailing Directions, &c., to the time of high water at Dover. Full details of these streams are given in a book entitled "Tides and Tidal Streams of the British Islands"; the tidal streams are also shown in the Tidal Atlas, which consists of 12 charts (one for each hour of the tide at Dover), on which the mean direction of the stream at any place is indicated by an arrow, and the mean rates at the times of neap and spring tides are stated in knots.

When estimating the direction and rate of a tidal stream, it should be remembered that, although the direction and rate given are those which may be expected under ordinary conditions, the wind has a very great effect on tidal streams and tends to produce a surface current.

PART IV.—NAVIGATIONAL INSTRUMENTS.

CHAPTER XXIV.

THE MAGNETIC COMPASS.

THE MAGNETISM OF THE EARTH AND SHIP.

252. Magnetism.—In Parts I., II. and III. it has been assumed that the reader is acquainted with the principles of the various instruments which have been mentioned. In Part IV. we have to give an account of these instruments and to explain the methods by which their errors are allowed for or eliminated. The instrument on which the navigation of a ship chiefly depends is the compass, and this may be either a magnetic or a gyro-compass. In this and the two following chapters we shall deal with the magnetic compass, but as this instrument depends on the magnetism of the earth modified by that of the ship, we shall first give a general idea of magnetism.

Magnetism is the property of attracting iron which is peculiar to certain substances. It was first observed in a certain ore of iron called lodestone, which is found in many parts of the earth in connection with other iron ores. When a piece of this substance is brought near to small fragments of iron it attracts them ; a piece of such a substance is called a natural magnet.

Besides natural magnets there are artificial magnets which may be made by contact with natural magnets or by other means. Artificial magnets attract iron in the same way as natural magnets, and in either case the attraction is concentrated at two points, called poles, which in the case of a magnetised steel bar are situated very near the ends. Let us suppose that two artificial magnets whose poles are a, b and A, B have been made, and that in the process of manufacture a corresponds to A and b to B ; then it is found that, if the magnet ab be freely suspended, the pole A will repel the pole a and attract the pole b. This property of two magnets is generally stated in the form of a law—*Like poles repel, unlike poles attract one another.*

A pole of a magnet is said to be of unit strength if, when placed in air at a distance of one centimetre from a similar pole, it is repelled with a force of one dyne. It is found by experiment that, if the strengths of two poles are S and S', and D

is the distance between them, the force exerted by either pole on the other is

$$\frac{S \, . \, S'}{D^2},$$

and this force is an attraction or a repulsion according as the poles are unlike or like.

It is impossible to separate the two poles of a magnet, but for convenience we may suppose that the magnet *AB*, Fig. 192, is acting on a solitary pole *a*. This pole is under the action of two forces—a force of attraction in the direction *aB*, and a force of repulsion in the direction *Aa*; the resultant of these forces is in some direction *aC*, and this direction is called the direction of the line of force of the magnet *AB* at the point *a*. Similarly, if a large number of points, such as *a*, are considered, the directions of the lines of force of the magnet *AB* will be as shown in Fig. 193; the area over which the influence of the magnet is felt is called the field of the magnet. If a small magnet *ab*, whose influence on a large magnet *AB* is inappreciable, be freely suspended in the field of the magnet *AB*, it will take up a position along a line of force as shown in Fig. 194.

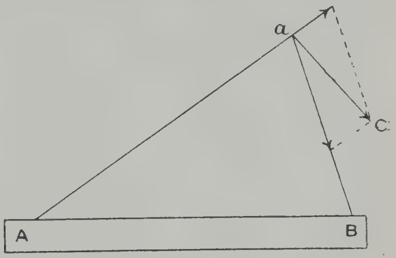


FIG. 192.

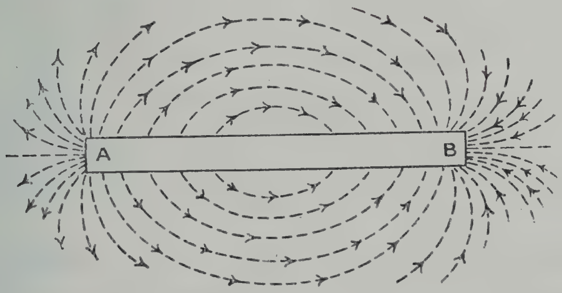


FIG. 193.

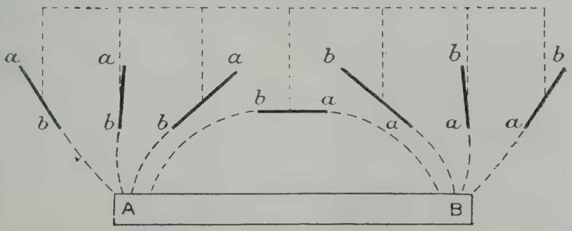


FIG. 194.

If the magnet *ab* be freely suspended at any place on the earth's surface, it will take up a definite position at that place; in North latitude one pole, *a* say, will point downwards and roughly in the direction of the North pole of the earth (Fig. 195); at the equator the magnet will be nearly horizontal, and in South latitude the pole *b* will point downwards and roughly in the direction of the South pole of the earth. From this and the law stated above we conclude that the earth is a natural magnet, and that its poles, called the North and South magnetic poles, are situated in the vicinity of the geographical poles. Thus we see that the magnetism of the pole *b*, which is at the South-seeking end of the magnet *ab*, is of the same nature as the magnetism at the North magnetic pole; so, in order to avoid confusion when using the terms North and South, the magnetism of the earth at the North magnetic pole is called blue magnetism and that at the South magnetic pole red magnetism. The magnetism of the pole *a* is, therefore, red and that of *b* blue.

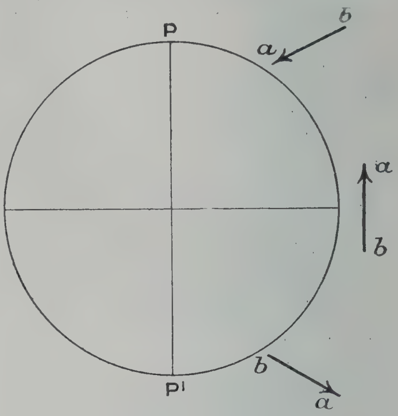


Fig. 195.

It will be convenient to consider that the lines of force of a magnet always proceed from the red pole to the blue, so that the direction of the lines of force of a magnet at any point in its field may be defined as being the direction in which a solitary red pole would travel under the influence of the magnet.

253. The effect of a magnet on an isolated pole.—Let *AB* (Fig. 196) be a small magnet of length $2l$ and pole strength S, and let O be an isolated red pole of unit strength, distant r from the centre of the magnet, r being so great compared with l that squares and higher powers of $\frac{l}{r}$ may be neglected. Let Ox and Oy be two rectangular axes, the former being parallel to the magnet. Let $COy = \theta$ and each of the angles AOC, COB (which are approximately equal) $= d\theta$.

$$\text{The pull of } B \text{ on } O = \frac{S}{(r - l\sin\theta)^2} \text{ along } OB.$$

$$\text{The push of } A \text{ on } O = \frac{S}{(r + l\,\text{s}^2\,\text{in}\theta} \text{ along } AO.$$

Therefore the force on O along Ox is

$$\frac{S}{(r - l\sin\theta)^2}\sin(\theta - d\theta) - \frac{S}{(r + l\sin\theta)^2}\sin(\theta + d\theta)$$

$$= \frac{S}{r^2} \cdot \frac{\sin\theta - d\theta\cos\theta}{(1 - \frac{l}{r}\sin\theta)^2} - \frac{S}{r^2} \cdot \frac{\sin\theta + d\theta\cos\theta}{(1 + \frac{l}{r}\sin\theta)^2}$$

$$= \frac{S}{r^2}\left[(\sin\theta - \frac{l}{r}\cos^2\theta)\,(1 + \frac{2l}{r}\sin\theta) - (\sin\theta + \frac{l}{r}\cos^2\theta)\,(1 - \frac{2l}{r}\sin\theta)\right]$$

$$= \frac{S}{r^2}\left[-\frac{2l}{r}\cos^2\theta + \frac{4l}{r}\sin^2\theta\right]$$

$$= \frac{Sl}{r^3}\,(1 - 3\cos 2\theta).$$

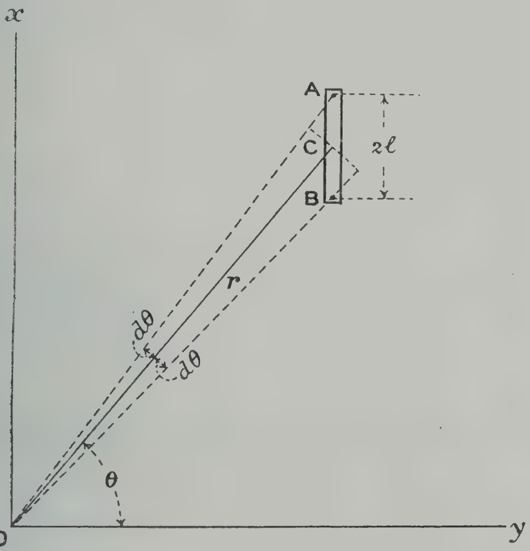


FIG. 196.

When $\theta = 90°$, this expression becomes $\frac{4Sl}{r^3}$, and when $\theta = 0°$ it becomes $-\frac{2Sl}{r^3}$; therefore the force due to the magnet in the direction Ox when "end on" is twice that due to the magnet when "broadside on," and in the opposite direction, as shown in Fig. 197.

Again, the force on O along Oy is

$$\frac{S}{(r - l\sin\theta)^2}\cos(\theta - d\theta) - \frac{S}{(r + l\sin\theta)^2}\cos(\theta + d\theta)$$

$$= \frac{S}{r^2} \cdot \frac{\cos\theta + d\theta\sin\theta}{(1 - \frac{l}{r}\sin\theta)^2} - \frac{S}{r^2} \cdot \frac{\cos\theta - d\theta\sin\theta}{(1 + \frac{l}{r}\sin\theta)^2}$$

$$\frac{S}{r}\left[\left(\cos\theta + \frac{l\cos\theta\sin\theta}{r}\right)\left(1 + \frac{2l}{r}\sin\theta\right) - \left(\cos\theta - \frac{l\cos\theta\sin\theta}{r}\right)\left(1 - \frac{2l}{r}\sin\theta\right)\right]$$

$$= \frac{S}{r^2}\left[\frac{6l\sin\theta\cos\theta}{r}\right]$$

$$= \frac{Sl}{r^3}\,3\sin 2\theta.$$

This expression vanishes when $\theta = 0°$ and $90°$.

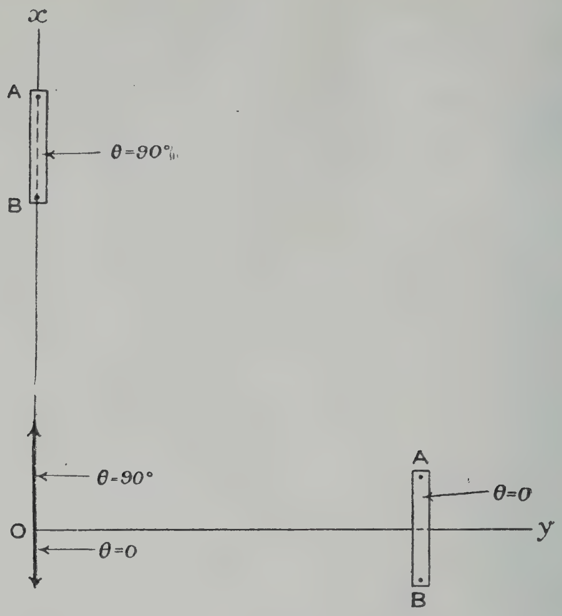


Fig. 197.

254. The molecular theory of magnetism.—If a magnet is cut in two it is found that each of the parts is itself a magnet; and if these parts are again divided the smaller parts are also magnets, and so on. It may therefore be concluded that if a magnet were broken up into its constituent molecules each of the molecules would be a very small magnet. The molecular theory of magnetism assumes that the molecules of a piece of iron are magnets. When the iron exhibits no external trace of magnetism the molecules are supposed to be lying among one another without any definite direction, but when the iron is magnetised the molecules all lie parallel to one another, all the red poles being directed to one end and all the blue poles to the other.

255. Magnetic induction.—Magnetic induction is the name given to the capacity which a magnet possesses for imparting magnetism to, or inducing magnetism in, a piece of iron placed in its field.

For the purpose under consideration iron may be divided into two kinds, hard and soft. Hard iron comprises those metals which offer considerable resistance to being magnetised, but if once magnetised they remain so. The property by virtue of which hard iron resists and retains magnetism is called its coercive force. Soft iron comprises those metals which instantly acquire magnetism when placed in a magnetic field, but which have no power of retaining it when the magnetic field is removed. So called soft iron is never so pure that there is not some small amount of magnetism remaining after the magnetic field has been removed, and this property is known as hysteresis. In Fig. 198 the iron rod *ab* is placed in the field of the magnet *AB* so that

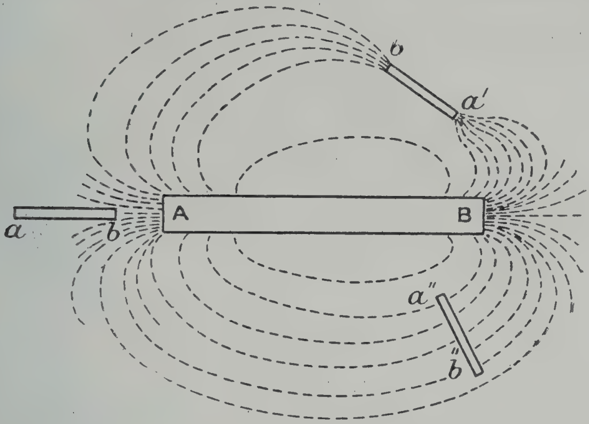


Fig. 198.

the lines of force pass directly through it and cause it to be magnetised as shown. When in the position *a′ b′*, the lines of force are deflected from their normal paths and pass through it producing magnetism as shown. It will be noticed that, since the lines of force are supposed to proceed from the red pole to the blue, the end of the iron rod at which the lines enter becomes a blue pole, and that at which they leave becomes a red pole. It will also be noticed that the lines of force tend to crowd together through the iron bar because iron is a better conductor of magnetism than air, and that in the immediate vicinity of the iron rod the lines of force, which do not enter it, are further apart than elsewhere. If the iron bar is placed in the position *a″ b″* so that its length is normal to the lines of force, no magnetism is induced if its diameter is small compared with its length.

If, instead of the iron rod *a b*, a soft iron ring, Fig. 199, were placed in the field of the magnet, the lines of force, following the

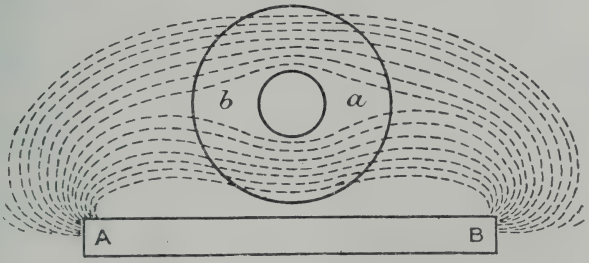


Fig. 199.

path of least resistance, would travel round the ring and emerge on the opposite side. Thus the effect of the ring would be to screen off the area within it from the effect of the magnet *AB*, and the ring would be magnetised as shown. If the ring were made to revolve, the poles *a*, *b*, would remain in the same places relative to the magnet *AB*, and therefore would apparently travel round the ring.

If, however, we suppose the metal of the ring to be intermediate between hard and soft iron, two poles *a′*, *b′*, Fig. 200, would be formed on the inside of the ring and lines of force would flow from *a′* to *b′* within the ring. If this ring were made to revolve, the four poles *a*, *b*, *a′*, *b′* would not exactly retain their positions relative to the magnet *AB* but would move slightly in the direction of rotation, and thus the direction of the lines of force within the ring would be slightly altered; this effect is of considerable importance, as will be explained in § 304.

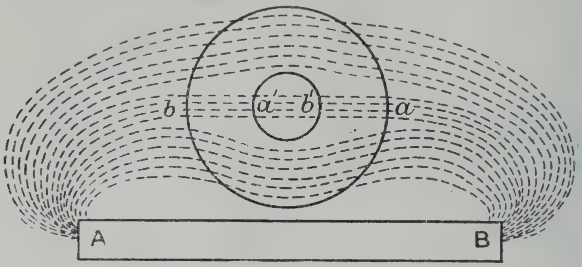


FIG. 200.

256. Artificial magnets.—We have now to explain how artificial magnets are made, and in order that they may be of a permanent nature, a special alloy, consisting of steel with the addition of 5 per cent. of tungsten, is used, because the most powerful magnets can be produced from this on account of its great coercive force.

(*a*) *By percussion.*—In Fig. 198 if the bar *a′b′* is of hard iron and is held in the direction of the lines of force of the powerful magnet *AB* it will not become magnetised, on account of its coercive force; a succession of blows from a hammer, however, assists the molecules, which are very small magnets, to take up a position parallel to one another, and the bar as a whole becomes a magnet. This method is not employed in the manufacture of artificial magnets, but advantage is taken of the property of magnetic induction mentioned above, various processes being employed, the most important of which are:—

(*b*) *By single touch.*—In Fig. 201 let *ab* be a bar of hard iron which it is desired to magnetise. The bar *ab* is stroked with a powerful permanent magnet *AB* as shown in the Figure, the direction of movement being always the same; *ab* becomes magnetised as shown, the end *b*, where the rubbing magnet leaves, acquiring opposite magnetism to the rubbing pole *A*.

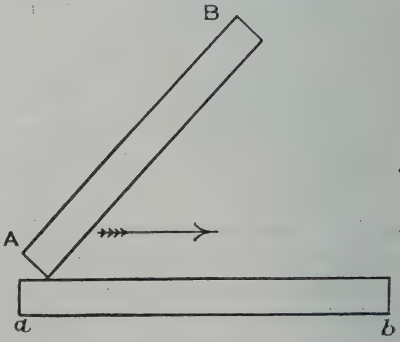


FIG. 201.

(*c*) *By separate or divided touch.*—The bar of hard iron *ab* is, in this case, stroked from its centre to its ends with two powerful permanent magnets *AB* and *A′B′* as shown in Fig. 202. The bar becomes magnetised as shown, each end acquiring opposite magnetism to that of the rubbing pole.

Magnets of small power are frequently made by this or the preceding method.

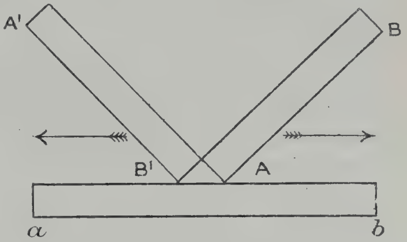


Fig. 202.

(*d*) *By electric current.*—Around a wire through which an electric current flows there is a magnetic field, the lines of force being concentric circles whose planes are perpendicular to the wire. Thus, if an electric current is flowing from the positive to the negative pole in the direction shown by the arrow in Fig. 203, and if *CD* is a plane perpendicular to the wire, the lines of force in the plane *CD* are the dotted circles shown, and their direction—that is, the direction in which a solitary red pole would move in the plane *CD*—is that shown by the curved arrow. The rule for finding the direction of the lines of force due to an electric current, is—swim with the current and face the solitary red pole, then your left hand indicates the direction.

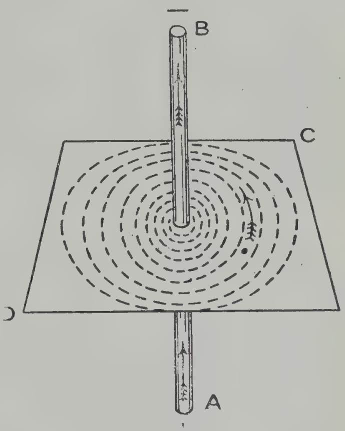


Fig. 203.

If the wire is bent into the form of a loop, as shown in Fig. 204, it will be seen that the directions of all the lines of force within the loop are the same; consequently, if a bar of hard iron is placed within the loop so that the lines of force flow through it, the bar will become magnetised as shown. When an artificial magnet is made in this manner, an insulated wire which carries the current is wound

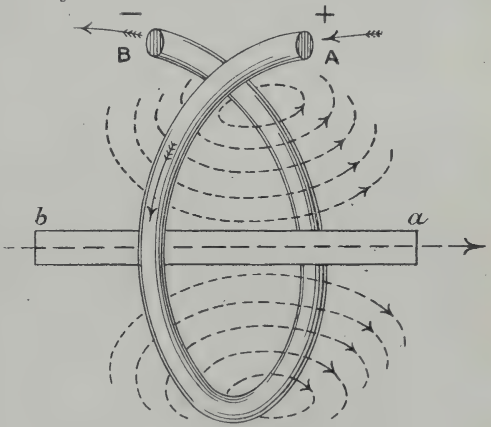


Fig. 204.

round the iron bar several times so as to strengthen the field. This method is employed for making powerful magnets such as those used for the correction of compasses, and needles for compasses of recent date.

257. Effects of temperature on magnets.—Magnets constructed of the alloy mentioned in § 256 retain their magnetic properties permanently, unless they are brought into an opposite magnetic field of great power or subjected to very high temperatures. If a permanent magnet is heated to a temperature between 1300° and 1500° F., it loses its magnetic properties, and the temperature at which this occurs is called the critical temperature for the particular metal of which the magnet is composed. Ordinary changes of atmospheric temperature have little or no effect on magnets. Raising the temperature of soft iron has the effect of greatly increasing its capacity for induction; thus, at a temperature of 1427° F. the capacity of soft iron is many times greater than at ordinary temperatures, but after further heating there is a rapid decrease until, at 1445° F., the iron is non-magnetic.

258. Terrestrial magnetism.—As stated in § 252, the earth is a huge natural magnet whose poles, as is found to be the case in all natural magnets, are unsymmetrically placed. The North (blue) magnetic pole is situated N.W. of Hudson Bay, and the South (red) magnetic pole in the Northern part of South Victoria Land. These magnetic poles are not fixed points on the earth but are constantly moving onward in unknown paths, and apparently complete a cycle in a period of many hundreds of years. Besides this onward movement of a few miles per annum the poles have a small daily oscillation.

The lines of force of the earth vary in direction from the vertical at the magnetic poles to the horizontal in the vicinity of the equator. A line drawn on the surface of the earth through all points where the lines of force are horizontal is called the magnetic equator, and this line may be assumed to be the line of division between the red and blue magnetism of the earth.

If a magnetic needle were freely suspended at any place under the influence of the earth's magnetism only, it would lie in the direction of the line of force at that place, and that great circle of the earth in the plane of which the needle would lie is called the magnetic meridian of that place; the angle between the meridian and the magnetic meridian of the place is the magnetic variation (§ 14).

The earth's magnetic force on a solitary red pole of unit strength at any place, called the total force at that place, acts along the line of force at that place, and this, as stated in § 252, is inclined at various angles to the earth's surface. The angle which the line of force at any place makes with the horizontal plane is called the dip at that place and will be denoted by θ.

It is convenient to resolve the total force at any place into its horizontal and vertical components, denoted by H and Z respectively, so that

$$\tan \theta = \frac{Z}{H}.$$

The earth's horizontal and vertical forces at any place are shown on charts, called charts of equal horizontal force and charts of equal vertical force respectively, by means of lines drawn through all points where the forces, expressed in c.g.s. units (dynes), are the same. The dip at any place is shown on a chart called the chart of equal magnetic dip, by means of lines drawn through all points where the dip is the same; these lines are sometimes called lines of equal magnetic latitude. The magnetic equator is the line of no dip, and the pecked lines on the chart, South of the magnetic equator, indicate that the South (blue) end of the needle is depressed.

Charts of equal horizontal and vertical force and of equal magnetic dip will be found in the Admiralty Manual for the Deviations of the Compass.

259. Changes in the variation.—The variation at any place is liable to regular and irregular changes, the regular changes being secular, annual, and diurnal.

The secular change.—The secular change of the variation is that which takes place over long periods, and from which the regular yearly change, given on the variation chart, is obtained.

The annual change.—From April to July, Westerly variation decreases and Easterly variation increases; the converse occurs during the remainder of the year. In May and October the variation, apart from its secular change, is about the same. During the winter months the changes are small.

The diurnal change.—From early morning till 1^h or 2^h P.M. in the Northern hemisphere the mean movement of the North (red) end of the needle is from East to West; from 2^h P.M. to 10^h P.M. it is from West to East, and during the night it is practically nil. In the Southern hemisphere the mean movements during the same intervals take place in the opposite directions. In the Northern hemisphere Westerly variation is greatest during the hottest part of the day. The diurnal change is smallest near the equator, where, in some places, it does not exceed 3′ or 4′, and it increases with the latitude. In England the diurnal change varies from 25′ in summer to 5′ in winter.

The irregular changes are said to be due to magnetic storms, which occur with great rapidity and cause deflections of the needle to the right and left. It is found that magnetic storms are nearly always accompanied by the exhibition of the auroræ in high latitudes (§ 196). It is extremely unlikely that a magnetic storm would cause an appreciable alteration of the variation, and probably the storm would only be manifested by a slight oscillation of the needle.

The magnetic variation is found at magnetic observatories, but a compass (called the landing compass) is supplied to each of H.M. ships, and by means of this instrument observations may be taken at any place where there are no observatories.

260. Obtaining the variation by observation on shore.—The method of obtaining variation on shore consists of taking bearings, with a compass, of objects whose true bearings can be found. The compass should be unaffected by any other magnetic field than that of the earth in order that the bearings shown by it may be magnetic; the difference between the compass and true bearings gives the variation.

The compass used for this purpose is called the landing compass, and consists of a bowl in which is mounted a compass card; the card is graduated as shown in Fig. 9, the graduations being given for every 20′. The card is supported on a hardened steel pivot by means of a sapphire cap screwed into the centre of the card; two pivots and two caps are supplied with each compass. An arrangement called a lifter is provided, by means of which the card can be raised above the pivot, when it is desired to move the compass to another position near by. This avoids the risk of damage to the cap or pivot, and the card need only be unshipped when the compass has to be moved a considerable distance. When not in use the card should be kept in the box provided for the purpose. On the top of the bowl is fitted a graduated ring which is free to revolve, and which carries sight vanes together with a magnifying prism by which the reading of the card is facilitated.

When selecting a place at which to take observations care should be taken that no iron ore, steel buildings, or other magnetic substances are in the vicinity. Having set up the compass in the selected position, bearings of several objects, more or less evenly distributed round the compass, should be taken, in order that the centering error of the card may be eliminated. If a spare compass card is provided the observations should be repeated with it, and in any case the observations should be repeated with another cap and pivot.

In order to obtain the true bearings of the various objects the true bearing of one of the objects should be obtained in the manner which will be described in § 261; the horizontal angles between that object and each of the other objects should then be measured, and thus the true bearings of all the objects deduced. The sextant may be used to measure the horizontal angles, and, if one object should be at a greater elevation than another, the angle should not be taken to the elevated object, but to a point vertically below it. The graduated verge-plate, fitted to the bowl of the landing compass, may also be used to obtain the horizontal angles. This plate is graduated from 0° to 360° in the direction of the hands of a watch; the reading of the index, which is fitted on the ring which carries the sight vanes, may be accurately determined by means of a magnifying glass and vernier. The index should be set to zero, and the bowl trained until the line of the sight vanes passes through the object selected. The bowl should then be clamped and the sight vanes trained on to each of the other objects in succession, the horizontal angle being read from the zero object on each occasion. The sight vanes should be subsequently trained on to the zero object in order to see if the bowl has been displaced.

261. To find the true bearing of an object by observation.— To find the true bearing of an object the horizontal angle between the sun and the object is found by observation, as well as the true bearing of the sun at the same instant. The best results are obtained with a theodolite because this instrument is constructed for accurately measuring horizontal angles; the method of using a theodolite will be found in works on surveying. When no theodolite is available the horizontal angle can be obtained by means of the verge-plate of the landing compass, the training of the sight vanes on the sun being facilitated by a small mirror which deflects the sun's rays into the horizontal plane. The zero having been set, as explained above, on to the selected object, the sight vanes should be trained so that the vertical thread exactly touches the right or left limb of the sun. At the same instant the altitude of the sun should be observed in an artificial horizon, or the time noted by the deck watch, in order that the azimuth of the sun may be calculated; since, however, the sextant is more reliable than the deck watch, it is preferable to observe the altitude. About ten observations should be taken, five to the right limb and five to the left.

Owing to the difficulty of determining whether the verge-plate of the landing compass is exactly horizontal, and because the sextant is a far more accurate instrument than the verge-plate, observations with the sextant, for determining the horizontal angle, are preferable.

As it is generally impossible to measure the horizontal angle between the sun and an object with a sextant, it is necessary to measure the angular distance between the object and a limb of the sun, and to calculate the horizontal angle from this and the apparent altitudes of the sun and object. As the angular distance is necessarily measured to a limb of the sun, the semi-diameter must be added or subtracted to obtain the angular distance to the sun's centre, according as the nearer or further limb has been observed.

Case 1.—*Object on the horizon.*—In Fig. 205, which is on the plane of the observer's horizon, let X' be the apparent place of the sun's centre—that is, the point of the celestial concave where it is intersected by the tangent to the ray of light at the observer's eye. Let X be the true place of the sun and O an object on the horizon; then in the triangle PZX the three sides are known and we have—

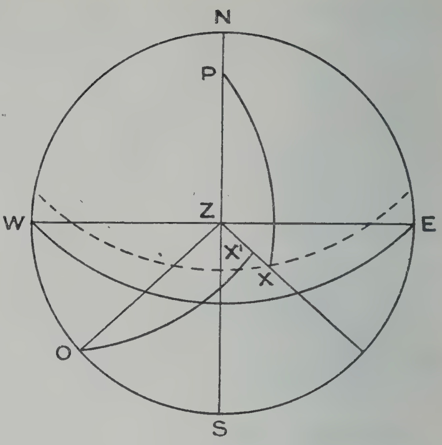


FIG. 205.

$$\text{hav}\, PZX = \text{cosec}\, PZ\, \text{cosec}\, ZX \sqrt{\text{hav}\,(PX + \overline{PZ\sim ZX})\, \text{hav}\,(PX - \overline{PZ\sim ZX})}$$

In the triangle OZX', ZO is 90° and we have—

$$\cos X'ZO = \cos OX'\, \text{cosec}\, ZX'$$

from which, since OX' is the angular distance, and ZX' is the complement of the apparent altitude, the angle $X'ZO$ can be found. With regard to this formula it may be useful to remember that $X'ZO$ is greater or less than 90° according as OX' is greater or less than 90°.

Case 2.—*Object elevated.*—When the object O is not on the horizon the angle $X'ZO$ may be found from the ordinary haversine formula.

The object O should be so selected that its angular distance from the sun is as nearly 90° as possible, because then a small error in the altitude of O will have the smallest effect on the horizontal angle OZX'.

262. Example of finding variation on shore.—On July 25th, 1914, at about 7^h A.M. M.T.P. at Wei-hai-wei, in latitude 37° 30′ 10″ N., longitude 122° 9′ 45″ E., the following observations were taken to determine the variation. The index errors of the sextants with which the altitudes and the angular distances were observed were respectively + 1′ 00″ and − 1′ 30″.

$\underline{\odot}$ 45° 00′ 30″ Beacon (on horizon) 95° 56′ 10″ $|\odot$
$\underline{\odot}$ 45 17 00 ,, 96 33 10 $|\odot$

Horizontal Angles.

Beacon 69° 00′ 40″ Centurion Flagstaff 72° 15′ 00″ Earthwork.
Earthwork 121° 37′ 50″ Lighthouse 64° 03′ 00″ Flagstaff.

Compass Bearings.

Beacon	N. 10° 10′ W.	Centurion Flagstaff	N. 58° 45′ E.
Earthwork	S. 49 00 E.	Lighthouse	S. 72 30 W.

Flagstaff N. 43° 30′ W.

To find the azimuth of the sun.

M.T.P.	19^h 00^m	July 24th	Dec. 20° 00′ 23″·3 N.	31·02
Long.	8 08	(E.).	5 37 ·2	10·87
G.D.	10 52	July 24th	19 54 46 N.	21714
			90 00 00	24816
				3102
			70 05 14 Polar distance	60/337·1874
				5′ 37″·2

	45° 00′ 30″		45° 17′ 00″
I.E. - -	+ 1 00	I.E. - -	+ 1 00
	2 /45 01 30		2 /45 18 00
App. alt. L.L.	22 30 45	App. alt. L.L.	22 39 00
S.D. - -	+ 15 46	S.D. - -	+ 15 46
App. alt. ☉ -	22 46 31	App. alt. ☉ -	22 54 46
Ref–Px - -	— 2 11	Ref–Px - -	— 2 10
True alt. -	22 44 20	True alt. -	22 52 36

Lat.	37° 30′ 10″	*L* sec 0·10055	Lat.	37° 30′ 10″	*L* sec 0·10055
Alt.	22 44 20	*L* sec 0·03514	Alt.	22 52 36	*L* sec 0·03558
	14 45 50			14 37 34	
Pol. dist.	70 05 14		Pol. dist.	70 05 14	
	84 51 04	½ *L* hav 4·82906		84 42 48	½ *L* hav 4·82848
	55 19 24	½ *L* hav 4·66674		55 27 40	½ *L* hav 4·66774
		9·63149			9·63235
Azimuth -	N. 81° 43′ 30″ E.		Azimuth -	N. 81° 49′ 30″ E.	

To find the true bearing of the beacon.

	95° 56′ 10″		96° 33′ 10″
I.E. - -	— 1 30	I.E. - -	— 1 30
	95 54 40		96 31 40
S.D. - -	+ 15 46	S.D. - -	— 15 46
	96 10 26		96 15 54

Ang. dist.	96° 10′ 26″	*L* cos 9·03162	Ang. dist.	96° 15′ 54″	*L* cos 9·03790
App. alt.	22 46 31	*L* sec 0·03526	App. alt.	22 54 46	*L* sec 0·03575
		L cos 9·06688			*L* cos 9·07365
Hor. Angle -	96° 41′ 55″		Hor. angle -	96° 48′ 15″	
Sun's Azimuth	N. 81 43 30 E.		Sun's Azimuth	N. 81 49 30 E.	
True bearing of beacon -	N. 14 58 25 W.		True bearing of beacon -	N. 14 58 45 W.	

To find the true bearings of the various objects.

Mean true bearing of Beacon	N. 14° 58′ 35″ W.	
Beacon	68 59 10	Centurion Flagstaff.
True bearing of Centurion Flagstaff.	N. 54 00 35 E.	
Centurion Flagstaff	72 13 30	Earthwork.
	126 14 05	
	180 00 00	
True bearing of Earthwork	S. 53 45 55 E.	
Earthwork	121 36 20	Lighthouse.
True bearing of Lighthouse	S. 67 50 25 W.	
Lighthouse	64 00 30	Flagstaff.
	131 51 55	
	180 00 00	
True bearing of Flagstaff	N. 48 08 05 W.	

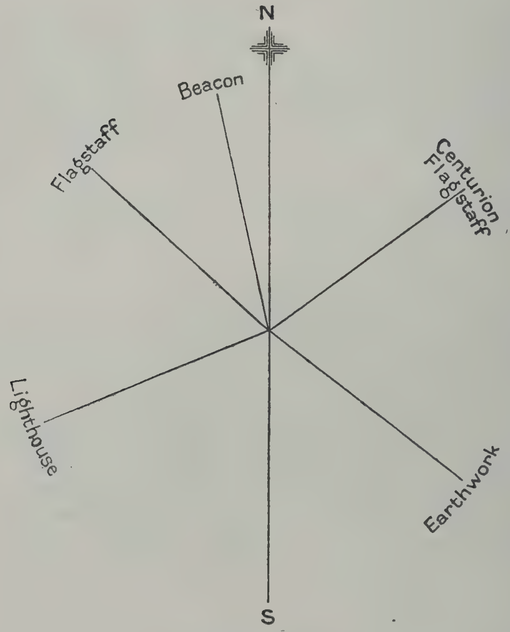


Fig. 206.

To find the mean variation.

	Beacon.	Centurion Flagstaff.	Earthwork.
True bearing	N. 14° 58′ 35″ W.	N. 54° 00′ 35″ E.	S. 53° 45′ 55″ E.
Compass bearing	N. 10 10 00 W.	N. 58 45 00 E.	S. 49 00 00 E.
Variation	4 48 35 W.	4 44 25 W.	4 45 55 W.

	Lighthouse.	Flagstaff.
True bearing -	S. 67° 50′ 25″ W.	N. 48° 08′ 05″ W.
Compass bearing -	S. 72 30 00 E.	N. 43 30 00 W.
Variation - -	4 39 35 W.	4 38 35 W.

4° 48′ 35″ W.
4 44 25 W.
4 45 55 W.
4 39 35 W.
4 38 35 W.

5 / 23 37 05

Mean Variation - 4 43 25 W.

263. Local attraction.—In a few places, where magnetic ore exists, the lines of force of the earth deviate considerably from their otherwise natural directions; therefore, in the immediate vicinity of such ore, the variation suddenly differs from that in the neighbourhood, and the attraction which causes the difference is called local attraction. The effect of a mass of magnetic ore can only be felt when very close to it, because the effect of one magnet on another varies inversely as the cube of the distance between them (§ 253), and we infer that no effect is likely to be felt on board a ship unless she happens to be in shallow water. It has been calculated that to produce an appreciable effect when a ship is in 30 fathoms of water a magnet of enormous power would be required. Thus it is obviously impossible for magnetic substances on shore to produce any effect on board a ship, unless she is extremely close to them. Information is given in the various Sailing Directions as to the places where local attraction has been found to exist. The most remarkable of these places is near Cossack in Western Australia where, in nine fathoms of water, the variation has been observed to vary from 56° E. to 26° W. in a distance of 200 yards.

264. The compass.—We have seen that at any place a freely suspended magnetised needle lies in the direction of the line of force at that place and, in general, is inclined to the horizontal plane. Since direction on the earth's surface is measured by a horizontal angle we require the compass card to lie horizontally; therefore the card with its needle (or system of needles) is suspended in such a way that its centre of gravity is vertically below the point of suspension. Now the forces acting on the compass needle (or needles) at any place are the earth's vertical force Z and the earth's horizontal force H; the effect of Z is counteracted by the particular method in which the compass card is suspended; the force H causes the needle to point in the direction of magnetic North at the place, and may therefore be termed the directive force of the earth at that place.

265. To compare the earth's horizontal force at two places.—The time of oscillation (T) of a compass needle when displaced in the horizontal plane from its mean position is given by

$$T = 2\pi\sqrt{\frac{I}{H.M}}$$

where I is the moment of inertia of the needle about its axis,
M is the magnetic moment of the magnet,
and H is the earth's horizontal force at the place.

If the compass needle is removed to a place where the earth's horizontal force is H', the time of oscillation (T') is given by

$$T' = 2\pi\sqrt{\frac{I}{H'.M}}$$

therefore

$$\frac{T^2}{T'^2} = \frac{H'}{H}.$$

Thus, if the times of oscillation of a compass needle are noted at two places, we see that the horizontal forces at the two places may be compared by means of this formula.

266. The permanent magnetism of a ship.—If a compass needle is brought into the field of a magnet, the directive force will be increased or decreased according as the lines of force of the magnet act with or against those of the earth. Now a ship, on account of the large amount of iron used in her construction, assumes the character of a large magnet, and therefore a compass on board a ship indicates direction under the action of two systems of lines of force—the system due to the earth which tends to make the needle lie in the magnetic meridian, and that due to the ship which tends to cause deviation. Before proceeding to deal with the deviation of the compass we must consider how the magnetism of the ship is acquired and distributed. The material of which a ship is constructed may be assumed to consist of hard and soft iron. On account of the earth's lines of force passing through a ship while she is being built, and the continual hammering to which the iron is subjected in the process of building, the hard iron becomes magnetised more or less permanently. When a ship is completed there appears to be an excess of magnetism, for it is found that, during the first few months at sea, she gradually loses a small amount, and finally settles down to a condition in which she may be regarded as a permanent magnet of constant strength.

The lines of force, travelling from South to North, produce a blue pole on the side of the ship at which they enter and a red pole on the side at which they leave; these poles are in the plane of the magnetic meridian of the place and also on the line of dip, but their positions, with regard to the fore-and-

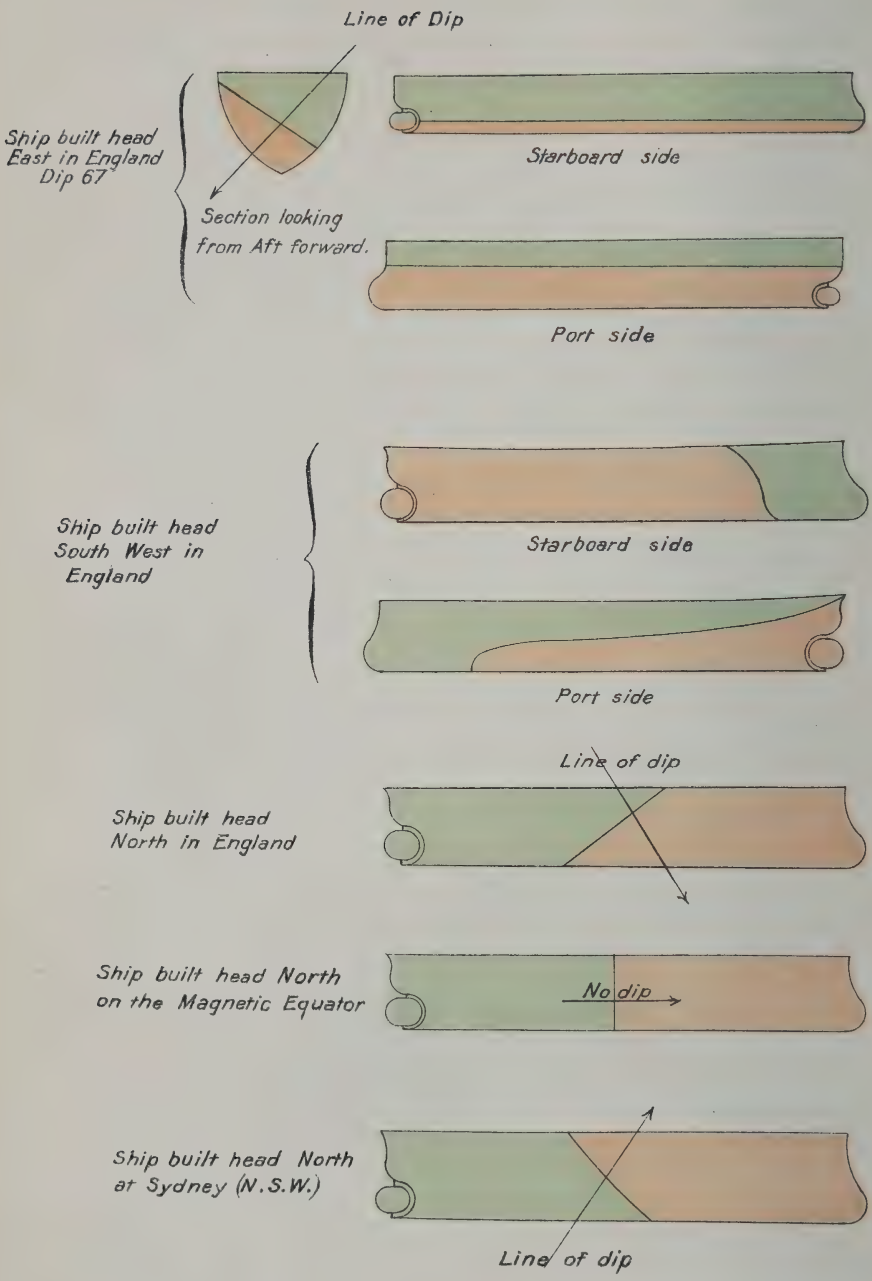

Line of Dip
Ship built head East in England Dip 67°
Section looking from Aft forward.
Starboard side
Port side
Ship built head South West in England
Starboard side
Port side
Line of dip
Ship built head North in England
Ship built head North on the Magnetic Equator
No dip
Ship built head North at Sydney (N.S.W.)
Line of dip

Fig 207.

38739 405. W B & L. 12/1/15

aft line, depend upon the direction of the ship's head when building. Fig. 207 shows approximately how the red and blue magnetism is distributed in a ship according to the magnetic latitude in which she was built and to the direction of her head when building.

The permanent magnetism of the hard iron of the ship induces magnetism in the soft iron, which is of opposite sign to the inducing force (§ 255) and equally permanent in character. Thus, the permanent magnetism of the ship may be regarded as the difference between the permanent magnetism of the hard iron and the magnetism induced by this in the soft iron.

Instead of regarding the ship as a magnet, it will tend to clearness if we suppose that the ship is free from all magnetism, but that she carries a magnet, as shown in Fig. 208 which represents a ship built in England (where the dip is 67°) with her head N.W. The effect of this magnet at the compass is the same as that of the permanent magnetism of the ship, and the direction in which it acts depends on the direction of the earth's lines of force at the place where the ship was built.

To investigate the effect of this magnet on the compass, we need only consider the force which is introduced at the North-seeking (red) end of the compass needle; this force, on account of the double symmetry of the ship, may be conveniently resolved into components in the fore-and-aft, athwartship, and vertical directions.

It is obvious that if we could place a similar magnet in contact with *NS*, but with its poles in the opposite directions, no effect would be felt at the compass. As it is impracticable to introduce such a magnet, a number of magnets are placed so close to the compass that they need only be of small strength, and in such a way as to counteract the components of the force at the compass due to the magnet *NS*.

In Fig. 208 the components of this force on the North-seeking (red) end of the compass needle are shown as *P*, *Q* and *R*, *P* being considered + when the pull on the North-seeking (red) end of the needle is forward, *Q* being + when the pull is to starboard and *R* + when the pull is downwards; when the pulls are in the opposite directions these forces are considered −. In Fig. 208 all the forces are negative.

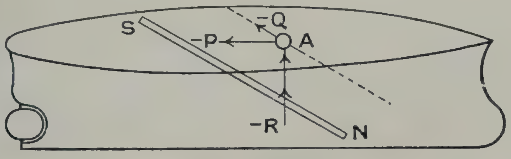


FIG. 208.

267. The induced magnetism of a ship.—Besides the hard iron of a ship there is a certain amount of soft iron which is always in a state of magnetisation, due to the earth's lines of force flowing through it; the amount and distribution of the induced magnetism depends on the ship's magnetic course. Thus, when the course is North, the forward end of a horizontal fore-and-aft bar of soft iron has red magnetism induced in it. When the course is N.E. the bar still has red magnetism at its forward end but of smaller amount. When the course is East there is no induced magnetism in the bar, since the lines of force are perpendicular to the bar. The magnetism induced in the bar when the course is North, North-East, East, &c. (magnetic) is as shown in Fig. 209.

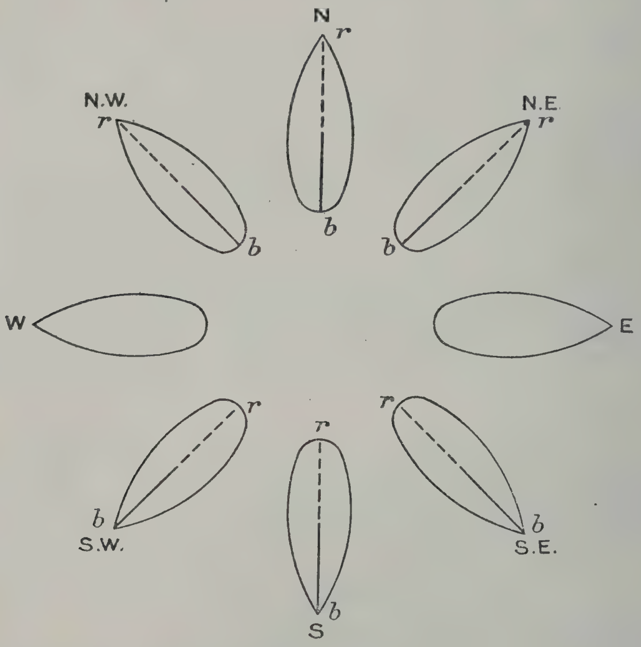


Fig. 209.

Thus we see that the magnetism induced in a soft iron bar in a ship depends on the angle between the bar and the lines of force of the earth; as this angle changes with every alteration of course the magnetism felt at the compass, due to this simple arrangement of soft iron, is subject to considerable variation.

As the soft iron of the ship lies in many directions it will be easily understood that the analysis of its effect at the compass presents considerable difficulties. These difficulties are partially surmounted by making the following assumptions:—

(1) The soft iron of a ship lies in three directions, fore-and-aft, athwartships, and vertical.

(2) The magnetism induced in soft iron is proportional to the inducing force.

To find the effect of the induced magnetism, it becomes necessary to find the components of the earth's total force in the three directions just mentioned. The vertical and horizontal components of the earth's total force are Z and H respectively (§ 258), so that we have to resolve H in the fore-and-aft and athwartship directions.

In Fig. 210 let Ox be the fore-and-aft line of a ship, the direction from O to x being forward and considered $+$. Let Oy be the athwartship line, the direction from O to y being to starboard and considered $+$. Let ON be the magnetic meridian, and let the angle NOx, which is the magnetic course measured from the magnetic meridian in an Easterly direction from 0° to 360°, be denoted by ζ.

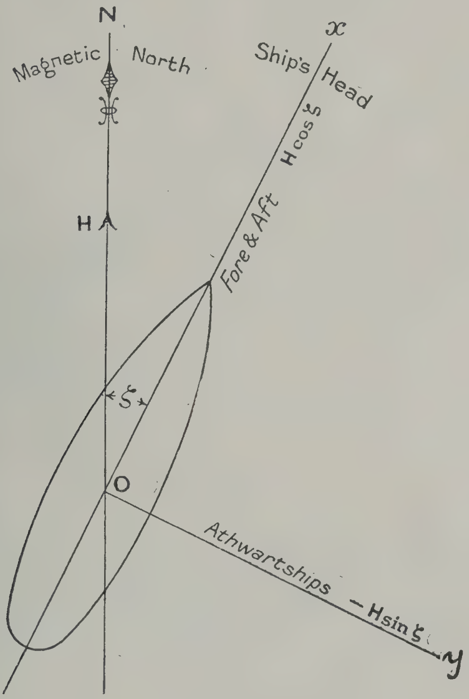


FIG. 210.

With these conventions as regards signs, it will be seen that the components of the earth's horizontal force, in the fore-and-aft and athwartship directions, are $H \cos \zeta$ and $-H \sin \zeta$ respectively. Therefore the components of the earth's total force, in the three perpendicular directions mentioned above, are as shown in Fig. 211.

From the above we see that the soft iron of the ship is magnetised by three forces :—

$H \cos \zeta$ fore-and-aft,
$-H \sin \zeta$ athwartships,
Z vertical ;

and in order to study the magnetism of the soft iron we shall deal with the effects of each of these forces separately. Let us first consider the effect of the fore-and-aft force $H\cos\zeta$ on the soft iron of the ship.

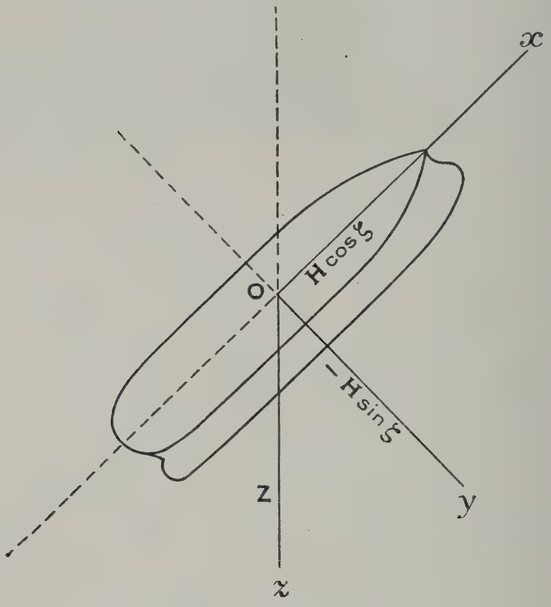


FIG. 211.

As explained in § 255, when a bar of soft iron is placed in a magnetic field the directions of the lines of force due to the magnetic field are modified in the vicinity of the soft iron, and the lines of force due to the magnetism induced in the bar are in the opposite direction to that of the inducing force. We may therefore consider that a similar result will occur when the fore-and-aft component of the earth's magnetism ($H\cos\zeta$) enters the soft iron of the ship, and we may conclude that the direction of the force at the compass, due to the induced magnetism, will not be in the fore-and-aft horizontal line but in some other direction. From the assumption (2) above the magnitude of the force at the compass will be $lH\cos\zeta$, where l is a constant depending on the soft iron of the ship.

In order to analyse the effect of this force at the compass we must resolve it into the three directions above mentioned. Let us suppose that the cosines of the angles which its direction makes with Ox, Oy and Oz (Fig. 212) are $\frac{a}{l}$, $\frac{d}{l}$ and $\frac{g}{l}$ respectively, then the resolved parts are

$$\begin{array}{ll} aH\cos\zeta & \text{along } Ox, \\ dH\cos\zeta & \text{along } Oy, \\ gH\cos\zeta & \text{along } Ox. \end{array}$$

In a similar way it may be shown that the athwartship force $-H \sin \zeta$ gives rise to three forces

$-bH \sin \zeta$ along Ox,
$-eH \sin \zeta$ along Oy,
$-hH \sin \zeta$ along Oz,

and that the vertical force Z gives rise to three forces

cZ along Ox,
fZ along Oy,
kZ along Oz.

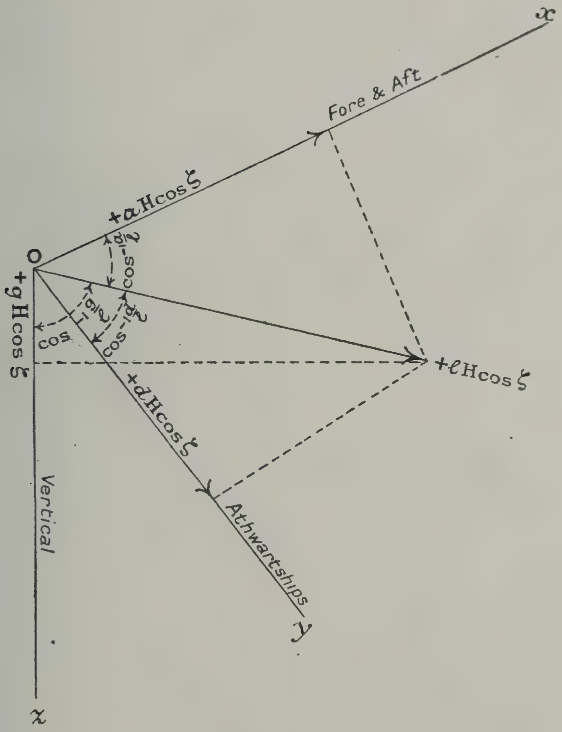


FIG. 212.

Thus the effect of the induced magnetism in the soft iron of the ship has been resolved into nine forces, as shown below :—

	Fore-and-Aft.	Athwartships.	Vertical.
Due to $H \cos \zeta$	$aH \cos \zeta$	$dH \cos \zeta$	$gH \cos \zeta$
,, ,, $-H \sin \zeta$	$-bH \sin \zeta$	$-eH \sin \zeta$	$-hH \sin \zeta$
,, ,, Z	cZ	fZ	kZ

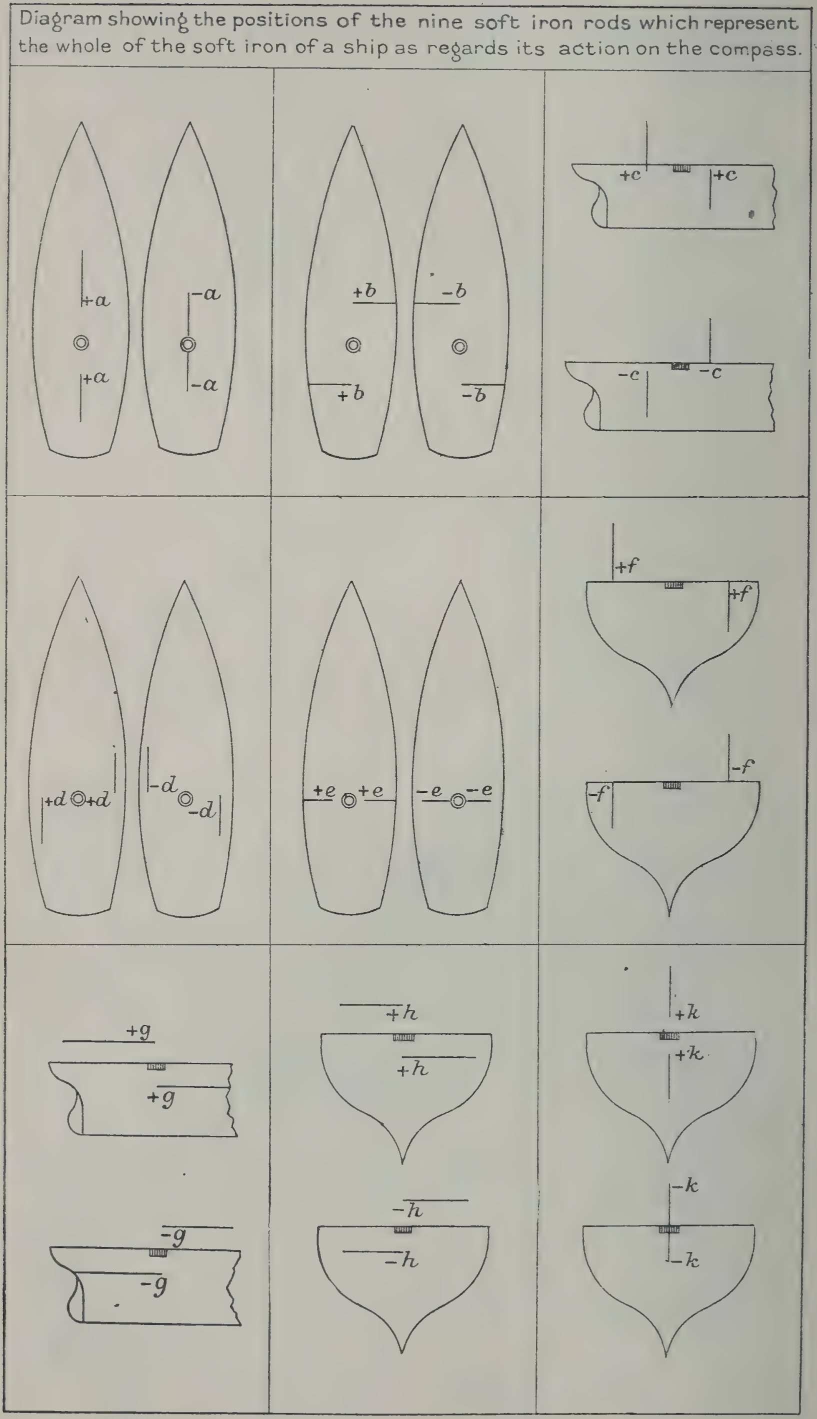


Diagram showing the positions of the nine soft iron rods which represent the whole of the soft iron of a ship as regards its action on the compass.
+a
+a
−a
−a
+b
+b
−b
−b
+c
+c
−c
−c
+d
+d
−d
−d
+e
+e
−e
−e
+f
+f
−f
−f
+g
+g
−g
−g
+h
+h
−h
−h
+k
+k
−k
−k

Fig. 213.

Therefore in a ship consisting of hard and soft iron the following forces act on the North-seeking (red) end of the compass needle:—

Due to the earth. $\left\{\begin{array}{l}\text{(1) } H \text{ in the magnetic meridian.}\\ \text{(2) } Z \text{ vertically downwards.}\end{array}\right.$

Due to the ship. $\left\{\begin{array}{l}\text{(3) } P + aH\cos\zeta - bH\sin\zeta + cZ \text{ in the fore-and-aft line.}\\ \text{(4) } Q + dH\cos\zeta - eH\sin\zeta + fZ \text{ athwartships.}\\ \text{(5) } R + gH\cos\zeta - hH\sin\zeta + kZ \text{ to keel.}\end{array}\right.$

In the last three expressions P, Q, and R are constants—generally called constant parameters—which depend on the amount, arrangement, and permanent magnetism of the hard iron of the ship; similarly, a, b, c, d, e, f, g, h, and k are constant parameters which depend on the amount, arrangement, and capacity for induction of the soft iron of the ship.

When considering the various forces due to the hard and soft iron of the ship, it is often convenient to represent them by permanent magnets and soft iron rods, the effects of which are the same as the forces which they represent. Fig. 213 shows the arrangement of the soft iron rods which correspond to the forces $\pm aH$, $\pm bH$, $\pm cZ$, &c.; the rod which has the same effect as $-aH$, for example, being named a $-a$ rod as in the Figure.

On examining the Figure it will be noticed that there is a great similarity between pairs: for example, the rods a and e are similarly situated with regard to the compass except that a is fore-and-aft and e athwartships. Similarly b and d may be taken together as well as c and f, and g and h.

268. The horizontal forces at the compass when the ship heels.—When a ship heels the hard and soft iron are differently situated with regard to the compass, and the soft iron is differently situated with regard to the earth's lines of force, so that the horizontal forces which act at the compass change when the ship is heeled.

Let i be the angle of heel of the ship, and let it be considered + or − according as the ship heels to starboard or port respectively.

When the ship heels the fore-and-aft line Ox, Fig. 211, does not change, but the athwartship line, Oy, and the line to keel, Oz, take up new positions, Oy', Oz', as in Fig. 214.

It was seen in the preceding article that the components of the earth's force along Ox, Oy and Oz are $H\cos\zeta$, $-H\sin\zeta$ and Z; when the ship heels, $-H\sin\zeta$ has a component $H\sin\zeta\sin i$ to keel and a component $-H\sin\zeta\cos i$ along Oy'; Z has a component $Z\sin i$ along Oy' and a component $Z\cos i$

to keel. Therefore, the total force to starboard along Oy' is

$$-H \sin \zeta \cos i + Z \sin i,$$

and the total force to keel along Oz'

$$Z \cos i + H \sin \zeta \sin i.$$

Therefore the inducing forces are,

along Ox $\quad H \cos \zeta,$
along Oy' $\quad -H \sin \zeta \cos i + Z \sin i$
and along Oz' $\quad Z \cos i + H \sin \zeta \sin i.$

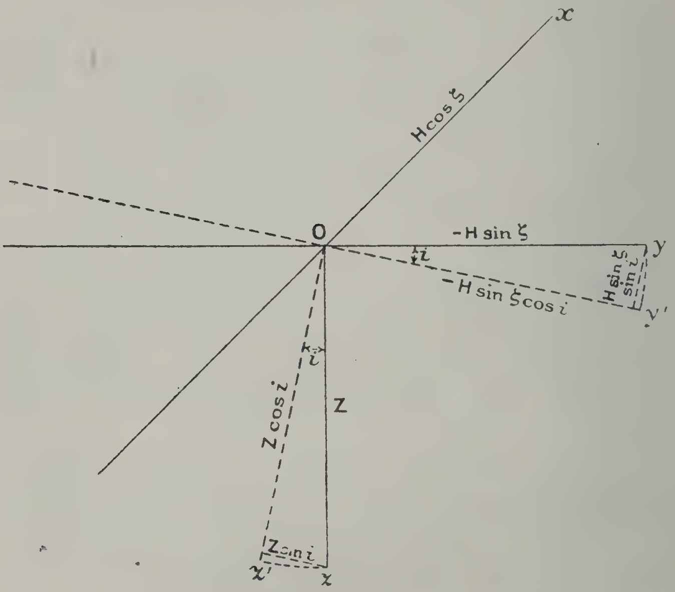


FIG. 214.

Therefore the components of the forces which act on the North end of the compass needle in these three directions may be found by substituting $-H \sin \zeta \cos i + Z \sin i$, for $-H \sin \zeta$; and $Z \cos i + H \sin \zeta \sin i$, for Z, in the expressions given in the preceding article where the ship was supposed to be upright. The components are as shown in Fig. 215, where it has been assumed that $b = d = f = h = 0$ and that the angle of heel i is so small that we may put $\sin i = i$, and $\cos i = 1$.

Now, since the compass needle is constrained to move in the horizontal plane, we have to resolve the forces which act along Oy' and Oz' into their components along the horizontal line Oy and we find that the force along Oy is

$$\text{the original force } - i.g.H \cos \zeta + i(eZ - kZ - R).$$

The force along Ox is

$$\text{the original force } + i.c.H \sin \zeta.$$

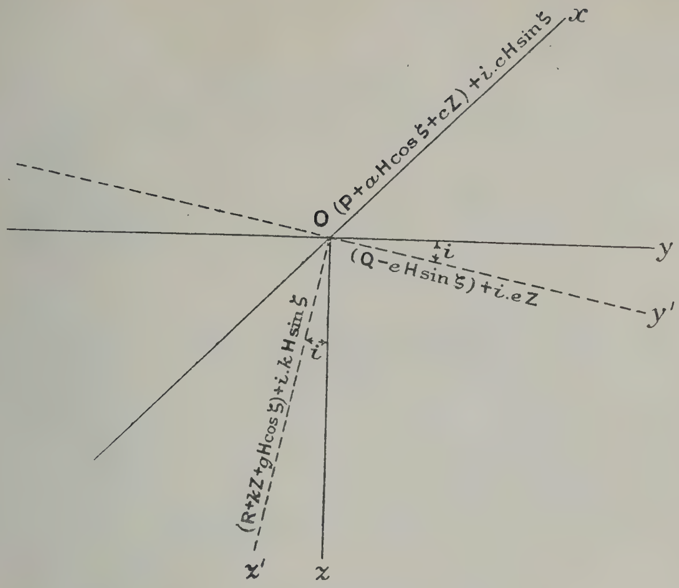


Fig. 215.

269. The sub-permanent magnetism of a ship.—In the expressions given above it has been assumed that the iron of the ship is either hard or soft. Now there is a certain amount of iron, used in the construction of a ship, which is neither hard nor soft but of a character intermediate between the two. Such iron, after lying for some time in the direction of the lines of force of the earth, and after being subjected to the vibrations of the engines and the firing of heavy guns, becomes magnetised by percussion. When the direction of the ship's head is changed the magnetism does not immediately disappear as in the case of soft iron, but suffers a gradual diminution which depends on the coercive force of the metal in question. Such magnetism is called sub-permanent magnetism and is generally small in amount. Thin iron superstructures, particularly when near heavy guns, are very liable to be magnetised sub-permanently Owing to the transient nature of this kind of magnetism, its amount cannot be calculated and its effect cannot be allowed for.

CHAPTER XXV.

THE MAGNETIC COMPASS—(*continued*).

THE ANALYSIS AND CORRECTION OF THE DEVIATION.

270. The deviation of the compass.—In addition to the earth's magnetism the compass needle is subjected to the influence of the permanent and induced magnetism of the ship; the effect is that the compass needle does not always lie in the magnetic meridian but generally to one or other side of it, and we have what is called deviation. Let us first examine the effect on a compass of a fore-and-aft permanent magnetic force $+P$.

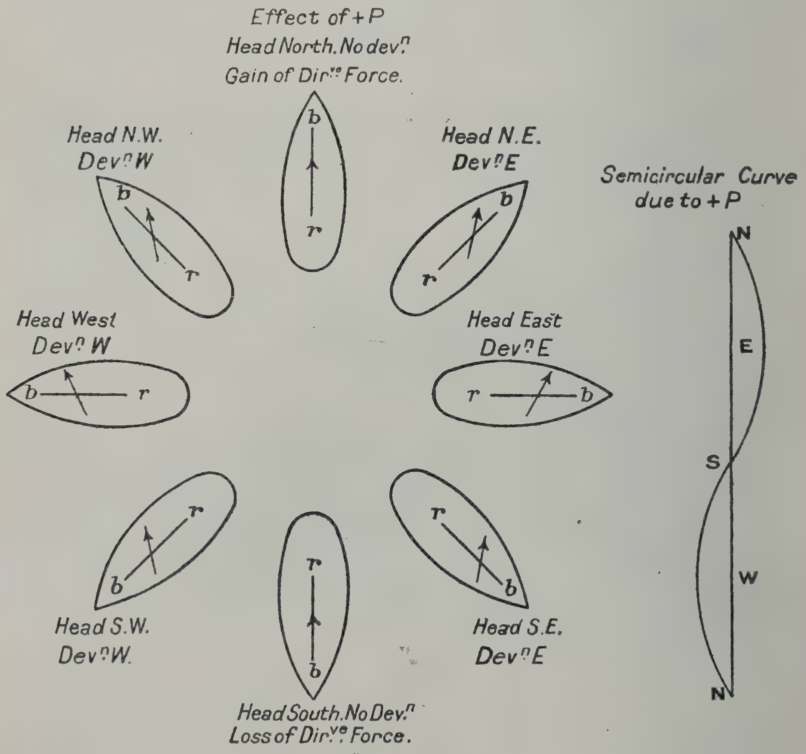


Fig. 216.

In Fig. 216 it will be seen that when the ship's head is North, the force $+P$ is acting with the earth's force, and we have what is called a gain of directive force. When the ship is on an Easterly course the compass needle is deflected to the

Eastward, and we have Easterly deviation. When the ship's head is south there is a loss of directive force, and when she is on a Westerly course there is Westerly deviation. Thus the deviation, due to this permanent magnetic force $+P$, changes with changes in the direction of the ship's head, and changes its name when the ship's head is directed in opposite semi-circles. Such deviation is called semi-circular, and may be represented by the abscissæ of the curve shown at the side of the Figure.

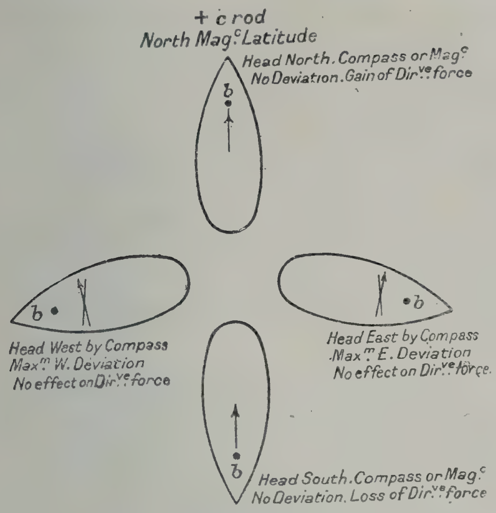

+ c rod
North Mag.c Latitude
Head North. Compass or Mag.c
No Deviation. Gain of Dir.ve force
b
Head West by Compass
Max.m W. Deviation
No effect on Dir.ve force
Head East by Compass
Max.m E. Deviation
No effect on Dir.ve force
Head South. Compass or Mag.c
No Deviation. Loss of Dir.ve force

FIG. 217.

In Fig. 217 is shown the effect of a $+c$ rod in the Northern hemisphere, where the induction in such a rod is to cause a blue pole before the compass. It will be seen that the effect is exactly similar to that of the permanent magnetic force $+P$ which was described above.

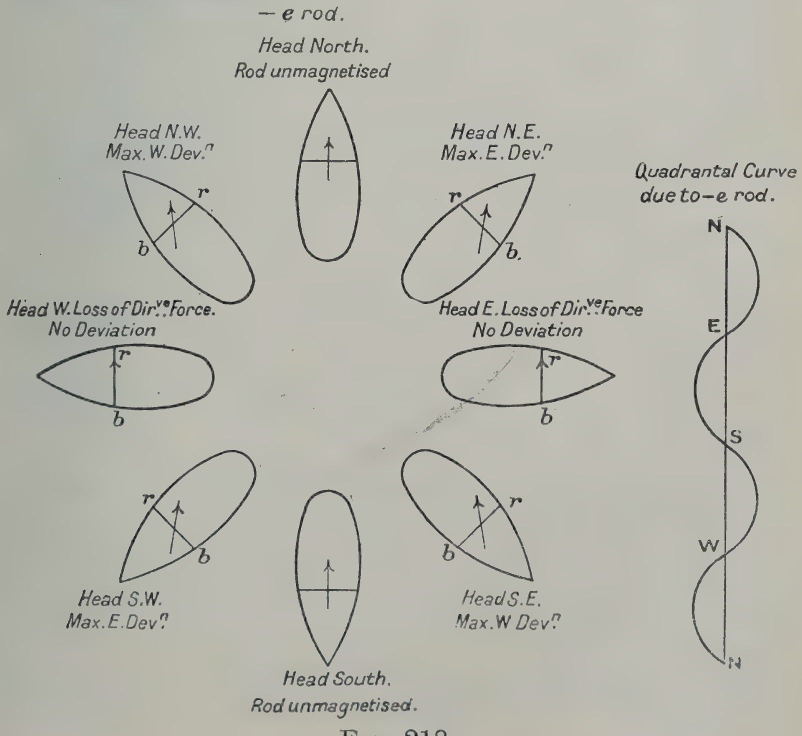


FIG. 218.

In Fig. 218 is shown the effect of a $-e$ rod. It will be seen that the effect of the induced magnetism in this rod is to cause a deviation of the compass when the ship is heading in any direction except a cardinal point, and that this deviation changes its name when the ship's head is directed in adjacent quadrants. Such deviation is called quadrantal, and may be represented by the abscissæ of the curve shown at the side of the Figure.

Similarly, figures could be drawn to show the effects of all the other forces mentioned in § 267. When these various forces co-exist, we see that the deviation of the compass varies considerably, both in amount and direction, with changes in the direction of the ship's head.

271. The principle of compass correction.—Owing to the large and varying values which the deviation may assume, great inconvenience would be caused by the necessity of applying it as a correction to every course steered or bearing taken; and it is obvious that if we could so arrange matters that the compass needle always remained in the direction of magnetic North the use of the compass would be greatly simplified. Now in order that there may be no deviation, it is necessary to introduce forces which will exactly counteract the effect of the ship's magnetism. A reference to §267 shows that the magnitudes of some of the forces, which cause deviation, change with every change of magnetic course and with changes in the geographical position of the ship, and therefore the forces to be introduced must be of such a nature that they change in a similar manner to the changes in the ship's magnetism, so that magnetism due to the hard iron of the ship must be counteracted by permanent magnets, and that due to the soft iron of the ship by soft iron correctors. It is obvious that the number and positions of such permanent magnets and soft iron correctors must depend on the magnitudes and directions of the forces which they are intended to counteract; for this reason we have to ascertain what part of the deviation is due to each of the several forces, in order that each part of the deviation may be corrected by a force which produces a corresponding deviation of opposite sign. We shall now express the deviation in terms of the forces which cause it, and the compass course.

272. The exact expression for the deviation of the compass.—Let ζ be the magnetic course measured from the magnetic meridian in an Easterly direction, and let ζ' be the compass course measured from the North point of the compass in a similar manner. Let δ be the deviation, + or − according as it is East or West; then $\delta = \zeta - \zeta'$.

The various forces which act on the North point of the compass needle—to magnetic North, to head and to starboard beam—are shown in Fig. 219 and the needle lies in the direction compass North under the action of these forces.

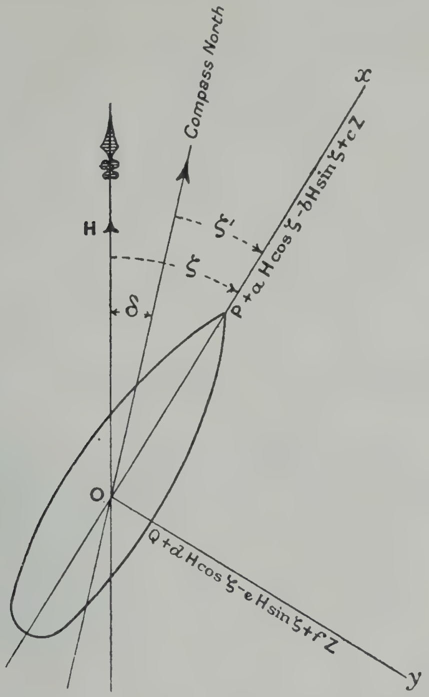


Fig. 219.

Since the needle is in equilibrium, the components of the forces in a direction perpendicular to the needle balance one another ; therefore

$$\begin{aligned} H \sin \delta &= (P + aH \cos \zeta - bH \sin \zeta + cZ) \sin \zeta' \\ &\qquad + (Q + dH \cos \zeta - eH \sin \zeta + fZ) \cos \zeta' \\ &= (P + cZ) \sin \zeta' + (Q + fZ) \cos \zeta' \\ &\quad + aH \cos \zeta \sin \zeta' - eH \sin \zeta \cos \zeta' \\ &\quad + dH \cos \zeta \cos \zeta' - bH \sin \zeta \sin \zeta' \end{aligned}$$

Now

$$\begin{aligned} \cos \zeta \sin \zeta' &= \tfrac{1}{2} [\sin (\zeta + \zeta') - \sin (\zeta - \zeta')] \\ &= \tfrac{1}{2} [\sin (2\zeta' + \delta) - \sin \delta] \end{aligned}$$

Similarly

$$\begin{aligned} \sin \zeta \cos \zeta' &= \tfrac{1}{2} [\sin (2\zeta' + \delta) + \sin \delta] \\ \cos \zeta \cos \zeta' &= \tfrac{1}{2} [\cos (2\zeta' + \delta) + \cos \delta] \\ \sin \zeta \sin \zeta' &= \tfrac{1}{2} [\cos \delta - \cos (2\zeta' + \delta)] \end{aligned}$$

Therefore

$$\begin{aligned} H \sin \delta = (P + cZ) \sin \zeta' &+ (Q + fZ) \cos \zeta' \\ &+ \frac{aH}{2} [\sin (2\zeta' + \delta) - \sin \delta] - \frac{eH}{2} [\sin (2\zeta' + \delta) + \sin \delta] \\ &+ \frac{dH}{2} [\cos (2\zeta' + \delta) + \cos \delta] - \frac{bH}{2} [\cos \delta - \cos (2\zeta' + \delta)] \end{aligned}$$

$$\begin{aligned}H\sin\delta &= (P + cZ)\sin\zeta' + (Q + fZ)\cos\zeta' \\ &\quad + H\left(\frac{a-e}{2}\right)\sin(2\zeta' + \delta) - H\left(\frac{a+e}{2}\right)\sin\delta \\ &\quad + H\left(\frac{d+b}{2}\right)\cos(2\zeta' + \delta) + H\left(\frac{d-b}{2}\right)\cos\delta\end{aligned}$$

$$\begin{aligned}\therefore H\left(1 + \frac{a+e}{2}\right)\sin\delta &= H\left(\frac{d-b}{2}\right)\cos\delta + (P + cZ)\sin\zeta' \\ &\quad + (Q + fZ)\cos\zeta' + H\left(\frac{a-e}{2}\right)\sin(2\zeta' + \delta) \\ &\quad + H\left(\frac{d+b}{2}\right)\cos(2\zeta' + \delta)\end{aligned}$$

Denoting $1 + \frac{a+e}{2}$ by λ, and dividing through by λH, we have

$$\begin{aligned}\sin\delta &= H\left(\frac{d-b}{2\lambda H}\right)\cos\delta + \left(\frac{P+cZ}{\lambda H}\right)\sin\zeta' + \left(\frac{Q+fZ}{\lambda H}\right)\cos\zeta' \\ &\quad + H\left(\frac{a-e}{2\lambda H}\right)\sin(2\zeta' + \delta) + H\left(\frac{d+b}{2\lambda H}\right)\cos(2\zeta' + \delta)\end{aligned}$$

Denoting the coefficients on the right by A', B', C', D' and E', we have

$$\sin\delta = A'\cos\delta + B'\sin\zeta' + C'\cos\zeta' + D'\sin(2\zeta' + \delta) + E'\cos(2\zeta' + \delta)$$

The right-hand side of this equation gives the sine of the deviation expressed nearly, though not wholly, in terms of the coefficients A', B', &c. (called the exact coefficients) and the compass course.

In the Admiralty Manual for the Deviations of the Compass the exact coefficients are denoted by old English letters.

273. The meaning of λ.—We shall now explain the meaning of the symbol λ, and as the force λH appears in each of the exact coefficients the symbol is of considerable importance.

Let H' be the directive force on the compass needle in the direction of compass North, then the force acting on the compass needle in the direction of magnetic North is $H'\cos\delta$.

Since the directive force to magnetic North is given by resolving the various forces shown in Fig. 219 along the magnetic meridian, we have

$$\begin{aligned}H'\cos\delta &= H + (P + aH\cos\zeta - bH\sin\zeta + cZ)\cos\zeta \\ &\qquad - (Q + dH\cos\zeta - eH\sin\zeta + fZ)\sin\zeta \\ &= H + (P + cZ)\cos\zeta - (Q + fZ)\sin\zeta \\ &\qquad + aH\cos^2\zeta + eH\sin^2\zeta - (d + b)H\sin\zeta\cos\zeta \\ &= H + (P + cZ)\cos\zeta - (Q + fZ)\sin\zeta + \left(\frac{a+e}{2}\right)H \\ &\qquad + H\left(\frac{a-e}{2}\right)\cos 2\zeta - H\left(\frac{d+b}{2}\right)\sin 2\zeta \\ &= \lambda H(1 + B'\cos\zeta - C'\sin\zeta + D'\cos 2\zeta - E'\sin 2\zeta)\end{aligned}$$

Now this equation is true whatever the value of ζ, so that, if we suppose the ship to be headed successively in every direction from 0° to 360°, and remember that the mean values of the trigonometrical ratios on the right are all zero, λH is the mean value of $H'\cos\delta$; that is, λH is the mean directive force to magnetic North at the place in question. Therefore λ is the ratio which the mean directive force to magnetic North at the compass needle bears to the earth's horizontal force at the place in question.

Since each of the exact coefficients varies inversely as λH we see that δ roughly varies inversely as λH. For this reason the position selected for the compass should be such that the value of λ is as large as possible.

It is found that on board ship the forces aH and eH are always such as to reduce the directive force, and consequently λ is always less than unity. The value of λ at a well placed compass often exceeds ·8, but at a badly placed compass it may be as small as ·2.

The value of λ does not alter appreciably in different parts of the world, but time and high temperature tend to slightly increase it.

274. The approximate expression for the deviation.—The form of the exact expression for the deviation, given in § 272, suggests that the deviation, when of only moderate amount, may be expressed in the simple and convenient form

$$\delta = A + B \sin \zeta' + C \cos \zeta' + D \sin 2\,\zeta' + E \cos 2\,\zeta',$$

where A, B, C, D and E are angles in degrees, and are called the approximate coefficients.

If δ is observed for various positions of the ship's head, the approximate coefficients may be found more easily from the equation above, than can the exact coefficients from the exact expression for the deviation. Therefore, if we find the approximate coefficients from observation, it is necessary to find the connection between the approximate and exact coefficients before we can ascertain the values of the various forces involved in the exact coefficients; but, before doing so, we shall consider the component parts of the deviation as given by the approximate expression.

275. The component parts of the deviation.—The deviation of the compass, as given by the approximate expression, consists of five terms, as follows:—

A, which is independent of the compass course and is called the constant deviation.

$B \sin \zeta'$, which is a maximum, + or −, when the ship's head is East or West, and vanishes when the ship's head is North or South.

This part of the deviation is given by the abscissæ of the curves shown in Fig. 220, and, as it changes its name in opposite semicircles, it is called semicircular.

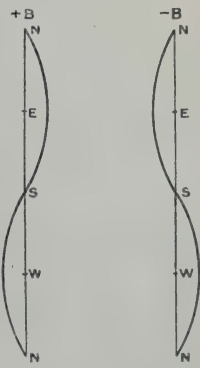


Fig. 220.

$C \cos \zeta'$, which is a maximum, + or −, when the ship's head is North or South, and vanishes when the ship's head is East or West.

This part of the deviation is given by the abscissæ of the curves shown in Fig. 221, and is also called semicircular.

The two parts $B \sin \zeta'$ and $C \cos \zeta'$ constitute the semicircular deviation of the compass, and the combination of the curves, (Figs. 220 and 221) gives the curve for the semicircular deviation; this curve is of similar form, but its maximum and minimum abscissæ do not, in general, occur at the cardinal points.

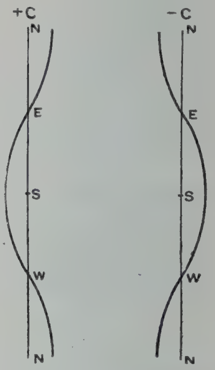


FIG 221.

$D \sin 2\zeta'$, which is a maximum when the ship's head is on either of the inter-cardinal points, and vanishes on the cardinal points.

This part of the deviation is given by the abscissæ of the curves shown in Fig. 222, and as it changes its name in adjacent quadrants, is called quadrantal.

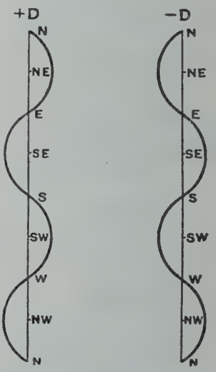


FIG. 222.

$E \cos 2\zeta'$, which is a maximum when the ship's head is on either of the cardinal points, and vanishes on the intercardinal points.

This part of the deviation is given by the abscissæ of the curves shown in Fig. 223, and is also called quadrantal.

The two parts $D \sin 2\zeta'$ and $E \cos 2\zeta'$ constitute the quadrantal deviation of the compass, and the combination of the two curves (Figs. 222 and 223) gives a curve for the quadrantal deviation which is of a similar form.

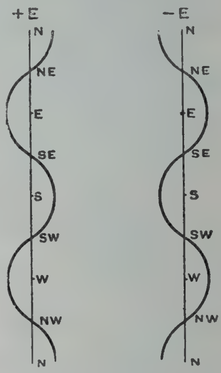


FIG. 223.

The total quadrantal deviation $D \sin 2\zeta' + E \cos 2\zeta$ may be expressed in the form $\sqrt{D^2 + E^2} \sin (2\zeta' + 2M)$, where $\tan 2M = \dfrac{E}{D}$. Therefore the maximum value of the quadrantal deviation is $\sqrt{D^2 + E^2}$.

276. Relations between the exact and approximate coefficients.—If, in the exact expression for the deviation, we put $\sin\delta = \delta$ and $\cos\delta = 1$, we have

$$\delta = A' + B' \sin\zeta' + C' \cos\zeta' + D' \sin 2\zeta' + E' \cos 2\zeta' \\ + \delta[D' \cos 2\zeta' - E' \sin 2\zeta'].$$

Therefore

$$\delta = (A' + B' \sin\zeta' + C' \cos\zeta' + D' \sin 2\zeta' \\ + E' \cos 2\zeta')\,(1 - D' \cos 2\zeta' + E' \sin 2\zeta')^{-1}.$$

As will be understood later, the coefficients A' and E' are always small compared with B', C' and D', so that we may consider B', C', D' to be small quantities of the first order and A', E' to be small quantities of the second order. Retaining small quantities of the second order only, we have

$$\delta = A' + B' \sin\zeta' + C' \cos\zeta' + D' \sin 2\zeta' + E' \cos 2\zeta' \\ + \frac{B'D'}{2}(\sin 3\zeta' - \sin\zeta') + \frac{D'C'}{2}(\cos 3\zeta' + \cos\zeta') - \frac{D'^2}{2}\sin 4\zeta' + \text{etc.}$$

On comparing the coefficients in this equation with those of the approximate expression, we have

$$\begin{aligned} A' &= \frac{\pi A}{180} = \sin A, \\ B' - \frac{B'D'}{2} &= \frac{\pi B}{180} = \sin B, \\ C' + \frac{C'D'}{2} &= \frac{\pi C}{180} = \sin C, \\ D' &= \frac{\pi D}{180} = \sin D, \\ E' &= \frac{\pi E}{180} = \sin E. \end{aligned}$$

From which it follows that

$$\begin{aligned} A' &= \sin A, \\ D' &= \sin D, \\ E' &= \sin E, \\ B' &= \frac{\sin B}{1 - \dfrac{D'}{2}} = \sin B\,(1 + \tfrac{1}{2}\sin D), \\ C' &= \frac{\sin C}{1 + \dfrac{D'}{2}} = \sin C\,(1 - \tfrac{1}{2}\sin D). \end{aligned}$$

More exact relations can be found, but these are sufficiently accurate in practice when the approximate coefficients do not exceed 10°.

277. To find the approximate coefficients from observation.—If the deviation of the compass is observed with the ship's head in various directions the approximate coefficients may be found from a short analysis of the deviation table.

Let $\delta_{\text{N.}}$, $\delta_{\text{N.E.}}$, $\delta_{\text{E.}}$, ... be the deviations observed with the ship's head successively on the eight-compass courses N., N.E., E., ..., then from the approximate expression for the deviation, namely—

$$\delta = A + B \sin \zeta' + C \cos \zeta' + D \sin 2 \zeta' + E \cos 2\zeta'$$

we have

Course	ζ'	δ	$= A + B \sin \zeta'$	$+ C \cos \zeta'$	$+ D \sin 2\zeta'$	$+ E \cos 2\zeta'$
N.	0°	$\delta_{N.}$	$= A$	$+ C$		$+ E$
N.E.	45	$\delta_{N.E.}$	$= A + \frac{B}{\sqrt{2}}$	$+ \frac{C}{\sqrt{2}}$	$+ D$	
E.	90	$\delta_{E.}$	$= A + B$			$- E$
S.E.	135	$\delta_{S.E.}$	$= A + \frac{B}{\sqrt{2}}$	$- \frac{C}{\sqrt{2}}$	$- D$	
S.	180	$\delta_{S.}$	$= A$	$- C$		$+ E$
S.W.	225	$\delta_{S.W.}$	$= A - \frac{B}{\sqrt{2}}$	$- \frac{C}{\sqrt{2}}$	$+ D$	
W.	270	$\delta_{W.}$	$= A - B$			$- E$
N.W.	315	$\delta_{N.W.}$	$= A - \frac{B}{\sqrt{2}}$	$+ \frac{C}{\sqrt{2}}$	$- D$	

By addition

$$8A = \delta_{N.} + \delta_{N.E.} + \ldots\ldots + \delta_{N.W.},$$

so that A is the mean of the deviations for the eight compass courses.

By subtracting the deviation for West from that for East, we have

$$2B = \delta_{E} - \delta_{W.}$$

In a similar manner

$$2C = \delta_{N.} - \delta_{S.}$$

By adding the deviations on the four intercardinal points, the signs of the deviations on S.E. and N.W. being changed, we have

$$4D = \delta_{N.E} - \delta_{S.E.} + \delta_{S.W.} - \delta_{N.W.}$$

Similarly by adding the deviations on the four cardinal points, the signs of the deviations on East and West being changed, we have

$$4E = \delta_{N.} - \delta_{E.} + \delta_{S.} - \delta_{W.}$$

It should be remembered that we have named Easterly deviation + and Westerly deviation – ; therefore, when using these algebraical signs, the signs of the coefficients are given by the equations.

The method of obtaining the approximate coefficients just given is called a rough analysis; a more exact method is given in the Admiralty Manual for the Deviations of the Compass.

As an example, let us find the approximate coefficients from the following observed deviations :—

Ship's head.	Deviation.	Ship's head.	Deviation.
N.	2° E.	S.	2° W.
N.E.	3 E.	S.W.	3 E.
E.	Nil.	W.	4 E.
S.E.	3 50′ W.	N.W.	1 50′ E.

We have from above:—

$$A = \frac{+2^\circ + 3^\circ + 0 - 3^\circ 50' - 2^\circ + 3^\circ + 4^\circ + 1^\circ 50'}{8} = +1^\circ$$

$$B = \frac{0^\circ - 4^\circ}{2} = -2^\circ$$

$$C = \frac{+2^\circ + 2^\circ}{2} = +2^\circ$$

$$D = \frac{+3^\circ + 3^\circ 50' + 3^\circ - 1^\circ 50'}{4} = +2^\circ$$

$$E = \frac{+2^\circ + 0 - 2^\circ - 4^\circ}{4} = -1^\circ$$

Therefore the deviation for any compass course is given approximately by

$$\delta = +1^\circ - 2^\circ \sin \zeta' + 2^\circ \cos \zeta' + 2^\circ \sin 2\zeta' - 1^\circ \cos 2\zeta'.$$

278. To find the exact coefficients.

—When the approximate coefficients have been found by the method of rough analysis or otherwise, the exact coefficients may be found from the relations given in § 276. In the example above, we have

$A' = \sin A = \sin 1^\circ = + \cdot 017.$

$B' = \sin B\,(1 + \tfrac{1}{2} \sin D) = \sin(-2^\circ)\,(1 + \tfrac{1}{2} \sin 2^\circ).$
$\quad = - \cdot 035\,(1 + \cdot 0175) = - \cdot 036.$

$C' = \sin C\,(1 - \tfrac{1}{2} \sin D) = \sin 2^\circ\,(1 - \tfrac{1}{2} \sin 2^\circ).$
$\quad = \cdot 035\,(1 - \cdot 0175) = + \cdot 034.$

$D' = \sin D = \sin 2^\circ = + \cdot 035.$

$E' = \sin E = \sin(-1^\circ) = - \cdot 017.$

279. The correction of coefficient B'.

$$B' = \frac{P + cZ}{\lambda H} = \frac{P}{\lambda H} + \frac{cZ}{\lambda H}.$$

From this formula we see that that part of the deviation, which is represented by the second term of the exact expression, arises from the fore-and-aft forces, P, due to the fore and aft component of the ship's permanent magnetism, and cZ, due to the fore-and-aft component of the induced magnetism due to Z, and represented by a c rod.

In order to counteract the effects of these two forces it is necessary to correct like with like, and to place at the compass a fore-and-aft permanent magnet which has an equal and opposite effect to P, and to place before or abaft the compass a rod of vertical soft iron the induction in which has an equal and opposite effect to cZ. To do this we must find P and cZ.

Let B_1' and B_2' be the exact coefficients at two places where the earth's horizontal and vertical forces are H_1, Z_1 and H_2, Z_2 respectively, then from above we have—

$$P + cZ_1 = \lambda H_1 B_1'$$
$$P + cZ_2 = \lambda H_2 B_2'$$

provided that nothing has been done between the two observations, such as moving the magnets, to alter the value of P. From these equations P and c may be easily found.

Screwed on to the binnacle is a brass case, in which can be placed a rod of soft iron, three inches in diameter and of the necessary length, to correct the effect of cZ. This rod is, in effect, a c rod of opposite sign to the c rod which represents the component of the induced magnetism under consideration. This soft iron corrector is called a Flinders bar, and is supplied in the following lengths—12, 6, 3, $1\frac{1}{2}$ ins. and two lengths of $\frac{3}{4}$ in., so that the greatest length that can be used is 24 ins.

In the Admiralty Manual for the Deviations of the Compass, Table V. gives the lengths of Flinders bar for values of c from ·01 to ·16, and also the amount of the deviation caused by these lengths at a compass on shore in the South of England, where the value of $\frac{Z}{H}$ is 2·33. The length of Flinders bar used should be placed in the tube in such a manner that the longest portion is uppermost, and the upper pole, which is about one-twelfth of the length of the bar from the extremity, is on a level with the compass needles; the latter is effected by placing pieces of wood of requisite length at the bottom of the tube.

It is obvious that if cZ has been counteracted by a correct length of Flinders bar it will always remain so whatever part of the world the ship may be in, because the force which induces magnetism in the ship is also that which induces magnetism in the Flinders bar. We see from this the importance of correctly placing the Flinders bar.

The finding of c requires two values of B' which correspond to different magnetic latitudes; when it is impossible for a ship to change her magnetic latitude, the value of c is estimated by comparison with the values obtained in other ships of the same class. A suitable length of Flinders bar is then inserted, and the remainder of the deviation, with the ship's head East or West, is corrected by permanent magnets placed in the fore-and-aft direction.

If B' is obtained by observation when the ship is on the magnetic equator the whole of B' is due to $\frac{P}{\lambda H}$ because Z is zero; in this case the whole of the deviation, with the ship's head East or West, should be corrected by permanent magnets. If a change of deviation subsequently occurs on change of magnetic latitude it is due to the Flinders bar being incorrect.

Example:—In 1912, the value of B' for the standard compass of a ship was found by observation at Plymouth and Zanzibar to be $+·141$ and $+·193$ respectively. The value of λ for the compass was ·9 and there was a 12-inch Flinders bar in place on the fore side of the binnacle. Required to correct the coefficient B'.

From the charts of equal horizontal and vertical force, we find that—

at Plymouth, $H_1 = \cdot 190$ dynes, $Z_1 = \cdot 425$ dynes.
at Zanzibar, $H_2 = \cdot 290$,, $Z_2 = -\cdot 210$,,

From the equations above we have—

$$P + \cdot 425c = \cdot 9 \times \cdot 190 \times \cdot 141 = \cdot 0241$$
$$P - \cdot 210c = \cdot 9 \times \cdot 290 \times \cdot 193 = \cdot 0504.$$

By subtraction, $\cdot 635c = -\cdot 0263$

$$\therefore c = -\frac{\cdot 0263}{\cdot 635} = -\cdot 041.$$

Now this value of c $(-\cdot 041)$ consists of the c due to the ship, and that due to the 12-inch Flinders bar which is already in place. From Table V. of the Admiralty Manual we see that a 12-inch Flinders bar, on the fore side of the binnacle, corrects a c which is $-\cdot 05$, so that this length of Flinders bar is equivalent to a c rod of $+\cdot 05$. Therefore

$$c \text{ of ship} + \cdot 05 = -\cdot 041;$$
$$\therefore c \text{ of ship} = -\cdot 091.$$

From Table V. we find that, corresponding to $-\cdot 091$, a length 16·3 inches of Flinders bar is required on the fore side of the binnacle.

Length of Flinders bar required -	- 16·3	inches.
,, ,, ,, already in place	12·0	,,
,, ,, ,, to be added -	4·3	,,

The nearest length to this, which can be made up from the lengths supplied, is $4\frac{1}{2}$ inches.

In practice the value of P is not found, but the remainder of the deviation, when the ship's head is East or West, is corrected by fore-and-aft permanent magnets. How to place these magnets in the binnacle is easily determined by noting in which direction, whether forward or aft, the North point of the needle should move, and by placing one (or more) of the corrector magnets (all of which are coloured red and blue) with its blue end in that direction, till the deviation vanishes.

280. The correction of coefficient C'.

$$C' = \frac{Q + fZ}{\lambda H} = \frac{Q}{\lambda H} + \frac{fZ}{\lambda H}.$$

From this formula we see that that part of the deviation, which is represented by the third term of the exact expression, arises from the athwartship forces, Q, due to the athwartship component of the ship's permanent magnetism, and fZ, due to the athwartship component of the induced magnetism due to Z and represented by an f rod.

At a well-placed compass in the midship line f is generally zero, and therefore C' is generally due to Q alone, and may be counteracted by placing an athwartship permanent magnet (or magnets) beneath the compass.

Q has its maximum effect when the ship's head is North or South, and therefore if the deviation is corrected by athwartship permanent magnets, when the ship's head is in either of these directions, the effect of Q is counteracted.

How to place the magnets in the binnacle is easily determined by noting in which direction, starboard or port, the North point of the compass needle should move, and by placing one (or more) of the corrector magnets, as necessary, with its blue end in that direction, till the deviation vanishes.

To summarise the rules given for counteracting the effects of P and Q, assuming that the Flinders bar has been correctly placed :—with the ship's head on any cardinal point, insert permanent magnets, as necessary, at right angles to the compass needle, and with their blue ends in that direction in which the North end of the compass needle should move ; repeat the operation on an adjacent cardinal point.

281. The correction of coefficient D' :—

$$D' = H\left(\frac{a - e}{2\lambda H}\right) = \frac{a - e}{2\lambda}.$$

From this formula we see that the deviation, represented by the fourth term of the exact expression, is due to the difference between the component in a fore-and-aft direction of the induced magnetism (represented by an a rod), and the component in an athwartship direction of the induced magnetism (represented by an e rod).

On board ship it is invariably found that these components are represented by $-a$ and $-e$ rods, and that the numerical value of e is considerably greater than that of a ; we therefore see that D' is always positive.

To counteract the effects of $-eH$ and $-aH$, soft iron spheres, called quadrantal correctors, are placed one on either side of the compass in the athwartship line, their centres being in the plane of the compass needles (§ 283). The spheres are hollow and their thickness is about one inch. Fig. 224 shows how the effect of the spheres counteracts the combined effects of the $-e$ and $-a$ rods.

From the formula, we see that D', or sin D, is the same in every part of the world, and therefore, if the soft iron spheres are so placed as to exactly counteract the effects of the $-e$ and $-a$ rods, this coefficient will be correct in all parts of the world.

Table IV. of the Admiralty Manual gives the sizes and positions of spheres required to correct various values of D in different types of compasses. To correct coefficient D' at a particular compass, enter the table for that compass with the value of D, found by observations of the deviations on the intercardinal points (§ 277), and find the size of the spheres and the distance from the side of the binnacle at which they should be placed.

When D' has once been corrected, it will remain so in all parts of the world, but this is only true if the compass needles are so short, and their magnetism so weak, that they produce no sensible induction in the spheres (§ 284).

It will be seen from the formula that D' is closely connected with λ, and therefore if D' is found to change from any cause, a change in λ may be expected.

As the deviation due to D' is quadrantal—that is to say, changes its sign in adjacent quadrants—the total deviation, if D is uncorrected, must vary considerably for small alterations of course, and thus we see the great necessity for the spheres being placed in position as accurately as possible. In the case of a new ship an estimation must be made of the value of D, and spheres placed accordingly. If, when observations have been taken on the intercardinal points, D is found to be zero, it is obvious that the estimation has been correctly made; but if an appreciable value of D is obtained the spheres require readjustment, as will be understood from the following example.

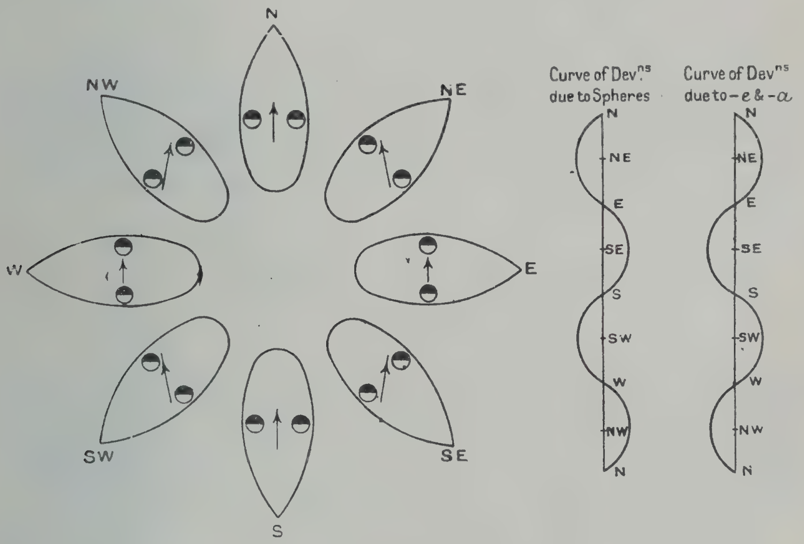

N
NW
NE
W
E
SW
SE
S
Curve of Dev.ns due to Spheres
N
NE
E
SE
S
SW
W
NW
N
Curve of Devns due to − e & − a
N
NE
E
SE
S
SW
W
NW
N

Fig. 224.

Example :—Spheres, $8\frac{1}{2}$ inches in diameter, have been placed on a Chetwynd compass (Patt. 22), the distance between the surface of either and the centre of the compass being 9 inches. The following deviations have been found by observation :—

Ship's head	-	N.E.	Deviation	2° 15′ W.
,,	-	S. E.	,,	0 30 W.
,,	-	S. W.	,,	0 45 W.
,,	-	N.W.	,,	3 30 E.

Required to correct coefficient D'.

From (§ 276)

$$D = \frac{-2^\circ\,15' + 0^\circ\,30' - 0^\circ\,45' - 3^\circ\,30'}{4}$$

$$\therefore D = -1^\circ\,30'.$$

From Table IV. of the Admiralty Manual we find that the spheres, as placed, correct a D of 6° 30′, or cause a $-D$ of 6° 30′.

Thus we have

D obtained by observation -	$-1^\circ\,30'$
D introduced by spheres -	$-6\;\;30$
Original D of the ship - -	$+5\;\;00$

By reference to Table IV. we find that $8\frac{1}{2}$-inch spheres at a distance of 10 inches from the compass, or 7-inch spheres at a distance of 9 inches, correct this value of D. Consequently, either the spheres at present in place must be moved outwards one inch, or they must be replaced by 7-inch spheres at a distance of 9 inches.

282. The correction of coefficient E'.

$$E' = H\left(\frac{d+b}{2\lambda H}\right) = \frac{d+b}{2\lambda}.$$

From the formula we see that the deviation, represented by the fifth term of the exact expression, is due to the sum of the component in a fore-and-aft direction of the induced magnetism (represented by a d rod), and the component in an athwartship direction of the induced magnetism (represented by a b rod).

It is very unusual for d or b to have any appreciable value at a well placed compass, but if E' is found to exist, it should be corrected, in conjunction with D', as explained in § 283, by placing the spheres at an angle M to the athwartship line, the angle being determined by

$$\tan 2M = \frac{E}{D}.$$

When E is + the port sphere should be forward, and when − the starboard sphere should be forward.

In order to determine the size of the spheres required and the distance of either from the compass, Table IV. of the Admiralty Manual should be entered with the maximum quadrantal deviation, namely

$$\sqrt{D^2 + E^2} \text{ (§ 275).}$$

283. The correction of the total quadrantal deviation.—In Fig. 225, let Ox and Oy be the fore-and-aft and athwartship lines of a ship, and let us consider the forces acting at a compass at O, due to the induction in a soft iron sphere of radius p, at a distance r from the compass, and at an angle M before the port beam.

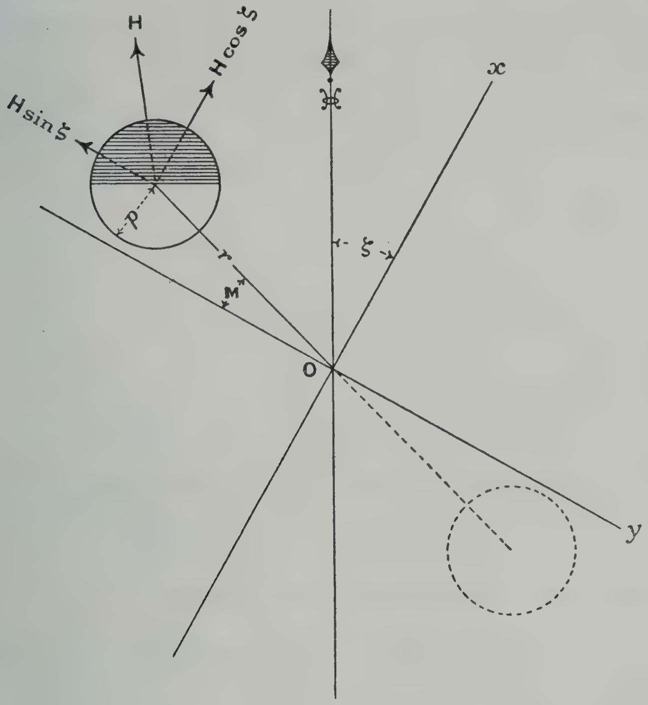


FIG. 225.

The inducing forces on the sphere are $H \cos \zeta$ and $-H \sin \zeta$ parallel to Ox and Oy respectively, and these cause the sphere to be equivalent to two magnets of pole strengths $\alpha p^2 H \cos \zeta$ and $-\alpha p^2 H \sin \zeta$ where α is a constant depending on the nature of the soft iron of the sphere. By § 253 the forces acting at the compass due to these two magnets are as follows:—

Due to	Force along Ox.	Force along Oy.
$ap^2H \cos \zeta$	$\frac{ap^3H \cos \zeta}{r^3} (1 - 3 \cos 2 M)$	$-\frac{ap^3H \cos \zeta}{r^3} 3 \sin 2M$
$-ap^2H \sin \zeta$	$\frac{ap^3H \sin \zeta}{r^3} 3 \sin 2M$	$-\frac{ap^3H \sin \zeta}{r^3} (1 + 3 \cos 2M)$.

If there are two spheres, as in the Figure, the forces along Ox and Oy are twice those just given, and the total force along Ox is

$$\frac{2ap^3H}{r^3} \left[(1 - 3 \cos 2M) \cos \zeta + 3 \sin 2M \sin \zeta\right]$$

and the total force along Oy is

$$-\frac{2ap^3H}{r^3}\Big[3\sin 2M\cos\zeta + (1+3\cos 2M)\sin\zeta\Big]$$

Comparing these forces along Ox and Oy with those due to the induced magnetism in the soft iron of the ship (§ 267), we have, if a', b', d', e' are the parameters for the spheres corresponding to a, b, d, e for the ship,

$$a' = \frac{2ap^3}{r^3}(1-3\cos 2M),$$

$$e' = \frac{2ap^3}{r^3}(1+3\cos 2M),$$

$$b' = d' = -\frac{2ap^3}{r^3}\,3\sin 2M.$$

Also, if λ' corresponds to λ, we have

$$\lambda' = 1 + \frac{a'+e'}{2} = 1 + \frac{2ap^3}{r^3}.$$

Now the quadrantal terms due to the spheres are

$$\frac{a'-e'}{2\lambda'}\sin 2\zeta' + \frac{b'+d'}{2\lambda'}\cos 2\zeta'$$

and, substituting from above, these become

$$-\frac{6ap^3}{\lambda' r^3}\Big[\cos 2M\sin 2\zeta' + \sin 2M\cos 2\zeta'\Big].$$

Therefore, if the spheres correct the quadrantal terms due to the ship, namely

$$D'\sin 2\zeta' + E'\cos 2\zeta',$$

we have
$$-\frac{6ap^3}{\lambda' r^3}\cos 2M = -D'$$

and
$$-\frac{6ap^3}{\lambda' r^3}\sin 2M = -E'.$$

From these two equations we can find at what angle with the athwartship line the spheres should be placed, and the distance of either from the compass.

By division, we have

$$\tan 2M = \frac{E'}{D'}$$

$$= \frac{\sin E}{\sin D} = \frac{E\times\dfrac{\pi}{180}}{D\times\dfrac{\pi}{180}}$$

$$= \frac{E}{D}.$$

If $E = 0$ then $M = 0$, and the spheres should be placed athwartships. If E is negative the port sphere should be placed abaft the beam.

Again, by squaring and adding, we have

$$\left(\frac{6ap^3}{\lambda' r^3}\right)^2 = D'^2 + E'^2$$

Therefore, substituting for λ', we have

$$\frac{6a\,\dfrac{p^3}{r^3}}{1 + 2a\,\dfrac{p^3}{r^3}} = \sqrt{D'^2 + E'^2}$$

$$\therefore \frac{r^3}{p^3} = 2a\left[\frac{3}{\sqrt{D'^2 + E'^2}} - 1\right]$$

$$\therefore \frac{r}{p} = \sqrt[3]{2a\left[\frac{3}{\dfrac{\pi}{180}\sqrt{D^2 + E^2}} - 1\right]}$$

and when $E = 0$

$$\frac{r}{p} = \sqrt[3]{2a\left[\frac{3}{\dfrac{\pi D}{180}} - 1\right]}\,.$$

The equation shows that for a given maximum quadrantal deviation ($\sqrt{D^2 + E^2}$), and a given kind of soft iron (a), the ratio of the distance of either sphere to its radius can be calculated. This, however, is not done in practice on account of the induction in the spheres by the compass needles, and Table IV. of the Admiralty Manual has been constructed from the results of experiments with various types of compasses.

We may here notice the effect of induction in the Flinders bar by the earth's horizontal force. This bar, having an appreciable diameter (3 inches), may be considered to behave in the same way as a soft iron sphere, and, M being 90° or 270° in this case, the quadrantal terms, due to the equivalent sphere, reduce to

$$\frac{3ap^3}{\lambda' r^3}\sin 2\zeta'$$

which corresponds to a $+D$. For this reason, as well as for others (§§ 284 and 296), the coefficient D should be re-determined and the spheres moved, as necessary, whenever the length of the Flinders bar is altered.

284. The induction in the soft iron correctors due to the compass needles.—As stated in § 281, the quadrantal deviation, if properly corrected by the spheres, remains correct in all magnetic latitudes, provided that no appreciable magnetism is induced in the spheres by the compass needles. If F be the force at the compass, due to the magnetism induced in the spheres by the needles, when the compass course is ζ', and if the spheres are in the athwartship line, the quadrantal terms of the deviation due to the spheres reduce to

$$\frac{(a' - e')\,H + F}{2\lambda H}\sin 2\zeta', \text{ nearly}$$

$$= \frac{a' - e'}{2\lambda}\sin 2\zeta' + \frac{F}{2\lambda H}\sin 2\zeta',$$

the second term of which changes as the ship changes her magnetic latitude. For this reason, when long and powerful compass needles are employed, a change in the quadrantal deviation may be expected on change of magnetic latitude.

The effect of this induction can be seen by examining Table IV. If the needles of the Thomson compass, (in binnacle Patt. 48a), are so short and weak as to have no effect on the spheres, the table for this compass only gives the effect of the induction of the earth in the spheres; for example, 12-inch spheres at a distance 14·5 inches (from centre of compass to centre of sphere), cause or correct 10° 36′ of quadrantal deviation, whereas in the Chetwynd compass (Patt. 22a) the same spheres, at the same distance, cause or correct 12° 15′; thus the effect of the induction by the needles in England, where $H = \cdot 184$ dynes, is to cause or correct 1° 39′.

In a similar manner the compass needles induce magnetism in the Flinders bar, the effect being to accentuate the value of D and cause it to change with change of magnetic latitude. This effect, combined with that due to the earth's horizontal force (§ 283), was found to introduce a D of + 1° 40′ when $11\frac{1}{4}$ inches of Flinders bar was placed before a compass, the D of which had previously been exactly corrected.

285. The coefficient A'.—

$$A' = H\left(\frac{d - b}{2\lambda H}\right) = \frac{d - b}{2\lambda}.$$

The coefficient A' represents the constant deviation and, since d and b are seldom found to have any value at a well placed compass, it is unusual at such a compass for A' to have any value. It is impracticable to counteract A', but when it exists at a steering compass, it may be allowed for, as far as the course alone is concerned, by altering the lubber's point.

286. To obtain λ by observation.—In order to obtain the value of λ at a particular compass, the value of H' (the directive force to compass North) must be observed for a particular direction of the ship's head, and this is done by timing the oscillations of a horizontal needle as explained in § 265. The instrument employed consists of a flat highly magnetised needle, three inches long, mounted in a circular box with a glass lid. The method of taking the observations is as follows:—take the instrument on shore and set it up in a place free from local attraction and sufficiently far removed from possible magnetic influences. Deflect the needle from the magnetic meridian by means of a magnet and allow it to oscillate. When the whole arc described by the needle is about 40°, note the instant when the North-seeking end (marked) has reached the extreme deflection on the right, and subsequently note the instant of every tenth oscillation, till the needle has nearly come to rest. The mean of the intervals occupied in ten oscillations is T (§ 265). Take the instrument on board and, having obtained the exact coefficients from the observed deviations, unship the compass bowl and place the instrument in the binnacle, so that its centre is in the position originally occupied by the centre of the system of compass needles; repeat the observation as on shore, and thus obtain the value of T' for the particular direction in which the ship's head happens to be. Then from § 265 we have

$$\frac{H'}{H} = \frac{T^2}{T'^2},$$

and λ may be obtained from the formula (§ 273)—

$$\lambda = \frac{H'}{H}\left(\frac{\cos\delta}{1 + B'\cos\zeta - C'\sin\zeta + D'\cos 2\zeta - E'\sin 2\zeta}\right)$$

It is advisable to repeat the operation for three or four different directions of the ship's head, and to take the mean of the results.

Should observations be taken on four equidistant points, λ is the mean of the four values of $\dfrac{H'\cos\delta}{H}$.

Example:—It is required to find the value of λ for the compass, the deviation table for which is given in § 15, and the exact coefficients for which have been found in § 278. The time of ten oscillations of the needle on shore is 18·2 seconds, and the time of ten oscillations of the needle on board, with the ship's head N. 67½° E. (compass), is 20·2 seconds.

Here $T = 18{\cdot}2$ seconds and $T' = 20{\cdot}2$ seconds.

From the table (§ 15) the deviation (δ) is 2° *E.* and therefore the magnetic course (ζ) is *N.* 69½° *E.*

$$\text{Now } \lambda = \frac{T^2}{T'^2}\left(\frac{\cos\delta}{1 + B'\cos\zeta - C'\sin\zeta + D'\cos 2\zeta - E'\sin 2\zeta}\right)$$

$$= \frac{18{\cdot}2^2}{20{\cdot}2^2}\left(\frac{\cos 2^\circ}{1 - {\cdot}036\cos 69\tfrac{1}{2}^\circ - {\cdot}034\sin 69\tfrac{1}{2}^\circ + {\cdot}035\cos 139^\circ + {\cdot}017\sin 139^\circ}\right)$$

$$= \frac{331{\cdot}24\cos 2^\circ}{408{\cdot}04\,(1 - {\cdot}0126 - {\cdot}0318 - {\cdot}0264 + {\cdot}0111)}$$

$$= \frac{331{\cdot}24\cos 2^\circ}{408{\cdot}04 \times {\cdot}9403}$$

$$= {\cdot}863.$$

Therefore the required value of λ is ·863.

287. The effect of spheres on λ and the formula for λ_2.—In Fig. 224, it will be seen that the effect of the spheres is to increase the directive force on the compass when the ship's head is East or West, and to decrease it when the ship's head is North or South, and therefore placing the spheres on the compass has almost always the effect of altering the mean directive force, or of altering λ.

The new value of λ is denoted by λ_2, the formula for which will now be obtained.

Let a' and e' be the values of a and e due to the spheres alone. Let a_2, e_2 and λ_2 be the values of a, e and λ after the spheres have been placed.

The fore-and-aft forces which induce magnetism in the spheres are

$H \cos \zeta$ due to the earth's magnetism.

$aH \cos \zeta$ due to the magnetism induced in the ship.

Therefore the fore-and-aft force which induces magnetism in the spheres is

$$H \cos \zeta + aH \cos \zeta.$$

The fore-and-aft force at the compass, due to the magnetism induced in the spheres by this force, is

$$a'(H \cos \zeta + aH \cos \zeta).$$

But, due to the inducing force $H \cos \zeta$ on the ship and spheres, the fore-and-aft force is

$$a_2 H \cos \zeta.$$

Therefore

$$a_2 H \cos \zeta = aH \cos \zeta + a'(H \cos \zeta + aH \cos \zeta),$$

or $$a_2 = a + a'(1 + a).$$

Similarly $$e_2 = e + e'(1 + e).$$

Now by § 283

$$\frac{a'}{e'} = \frac{1-3 \cos 2M}{1+3 \cos 2M},$$

therefore

$$\frac{a_2 - a}{e_2 - e} = \frac{(1-3 \cos 2M)(1+a)}{(1+3 \cos 2M)(1+e)}$$

Again, since D' has been corrected, $a_2 = e_2$ and therefore

$$\lambda_2 = 1 + a_2 \text{ or } 1 + e_2$$

Therefore

$$\frac{\lambda_2 - (1+a)}{\lambda_2 - (1+e)} = \frac{(1-3 \cos 2M)(1+a)}{(1+3 \cos 2M)(1+e)}$$

Now $$1 + \frac{a+e}{2} = \lambda$$

and $$\frac{a-e}{2} = \lambda D'.$$

Therefore, by addition and subtraction, we have

$$1 + a = \lambda\,(1 + D')$$

and

$$1 + e = \lambda\,(1 - D').$$

Therefore

$$\frac{\lambda_2 - \lambda\,(1+D')}{\lambda_2 - \lambda\,(1-D')} = \frac{(1-3\cos 2M)\,(1+D')}{(1+3\cos 2M)\,(1-D')}$$

$$\therefore \lambda_2\Big[(1+3\cos 2M)\,(1-D') - (1-3\cos 2M)\,(1+D')\Big]$$

$$= \lambda\Big[(1+3\cos 2M)\,(1-D'^2) - (1-3\cos 2M)\,(1-D'^2)\Big]$$

$$\therefore\ \lambda_2 = \frac{3\lambda\cos 2\,M\,(1-D'^2)}{3\cos 2\,M - D'}$$

When $M = 0$, we have

$$\lambda_2 = \frac{3\lambda\,(1-D'^2)}{3-D'}$$

From this formula it may be seen that λ_2 is greater than λ provided D' is less than $\frac{1}{3}$, which is generally the case.

288. The effect of sub-permanent magnetism.—The most marked effect of sub-permanent magnetism is experienced when the ship, having been on one course for a considerable time, particularly in rough weather, alters to a direction at right angles to her original course; for example, if a ship has been steaming East, the athwartship iron, the character of which is intermediate between hard and soft, becomes magnetised as shown in Fig. 226.

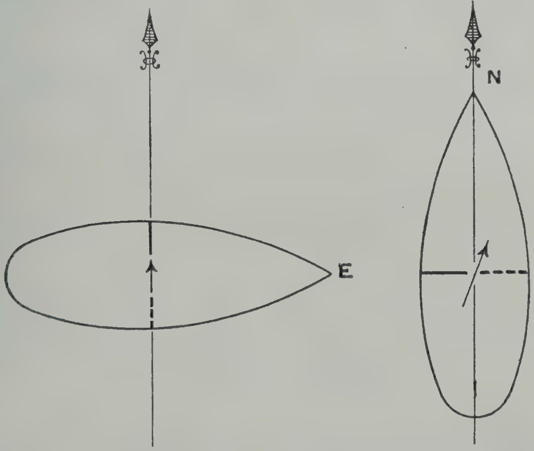


FIG. 226.

When the ship has altered course to North it will be seen that the sub-permanent magnetism remaining in this iron causes an Easterly deviation, which gradually disappears. If we were to consider other cases it would be found that the effect of sub-permanent magnetism is to attract the North end of the needle in the direction of the old course, and the possibility of this effect should be carefully guarded against by taking frequent observations for deviation. Suppose a ship were bound from England to Gibraltar; whilst crossing the Bay of Biscay and proceeding down the coast of Portugal the course would be more or less Southerly; but on altering course to the Eastward, to round Cape St. Vincent, an Easterly deviation would be caused, due to sub-permanent magnetism, and, if unallowed for, might result in the ship steering more to the Southward than desired.

289. The effect of lightning.—When a ship is struck by lightning, large changes take place in her magnetism, in some cases of sufficient magnitude to completely reverse the original magnetism. The change experienced in the deviation is generally a maximum when the ship's head is North or South, and consequently the most common effect of lightning is an alteration of the coefficient C'. The magnetism thus superimposed is generally sub-permanent; it gradually disappears, and the ship regains her original magnetic condition in a few months.

290. The expression for the deviation when the ship heels.—When the ship heels the horizontal forces (§ 268) which act on the North point of the compass needle—to magnetic North, to head and to starboard beam—are shown in Fig. 227, and the needle lies in the direction of compass North under the action of these forces. Let δ' be the deviation.

Since the needle is in equilibrium, the components of the forces in a direction perpendicular to the needle balance one another; therefore

$$\begin{aligned} H \sin \delta' &= (P + aH \cos \zeta + cZ) \sin \zeta' + (Q - eH \sin \zeta) \cos \zeta' \\ &\quad + icH \sin \zeta \sin \zeta' - igH \cos \zeta \cos \zeta' + i\,(eZ - kZ - R) \cos \zeta' \\ &= (P + cZ) \sin \zeta' + Q \cos \zeta' + aH \cos \zeta \sin \zeta' - eH \sin \zeta \cos \zeta' \\ &\quad + icH \sin \zeta \sin \zeta' - igH \cos \zeta \cos \zeta' + iZ \left(e - k - \frac{R}{Z}\right) \cos \zeta' \end{aligned}$$

Therefore, remembering that $\zeta = \zeta' + \delta'$, we have, as in § 272—

$$\lambda H \sin \delta' = (P + cZ) \sin \zeta' + Q \cos \zeta' + H \left(\frac{a - e}{2}\right) \sin (2\zeta' + \delta')$$
$$+ icH (\sin \zeta' \cos \delta' + \cos \zeta' \sin \delta') \sin \zeta' - igH (\cos \zeta' \cos \delta' - \sin \zeta' \sin \delta') \cos \zeta'$$
$$+ iZ \left(e - k - \frac{R}{Z}\right) \cos \zeta'$$

Now if δ' is so small that we may put $\sin \delta' = \delta'$, and $\cos \delta' = 1$, and neglect the product $i\delta'$, we have

$$\begin{aligned} \delta' &= B' \sin \zeta' + C' \cos \zeta' + D' \sin (2\zeta' + \delta') \\ &\quad + \frac{ic}{\lambda} \sin^2 \zeta' - \frac{ig}{\lambda} \cos \zeta' + \frac{iZ}{\lambda H}\left(e - k - \frac{R}{Z}\right) \cos \zeta'. \end{aligned}$$

Again, if δ is the deviation for a given compass course ζ' when the ship is upright, we have, by putting $i = 0$

$$\delta = B' \sin \zeta' + C' \cos \zeta' + D' \sin (2\zeta' + \delta).$$

Therefore

$$\delta' = \delta + \frac{ic}{\lambda} \sin^2\zeta - \frac{ig}{\lambda} \cos^2\zeta' + \frac{iZ}{\lambda H}\left(e - k - \frac{R}{Z}\right)\cos \zeta'.$$

If we assume that the Flinders bar has been correctly placed the expression $\frac{ic}{\lambda} \sin^2\zeta'$ vanishes, and the change in the deviation $(\delta' - \delta)^\circ$ for an angle of heel i° is

$$i\left[\frac{Z}{\lambda H}\left(e - k - \frac{R}{Z}\right) \cos \zeta' - \frac{g}{\lambda} \cos^2 \zeta'\right] \text{ degrees.}$$

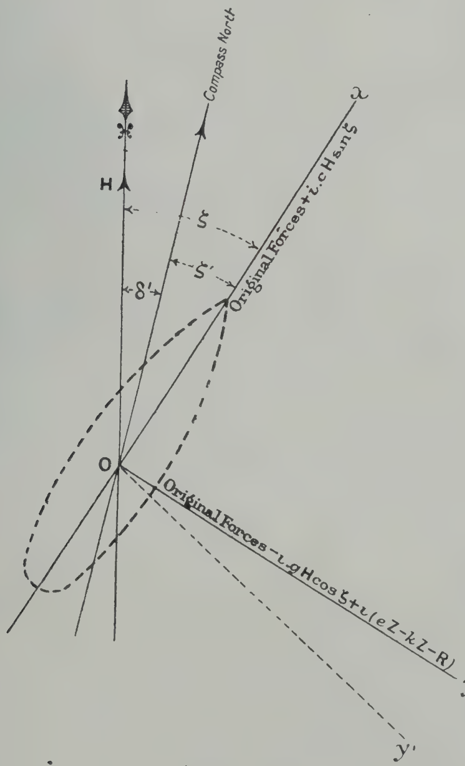


FIG. 227.

Therefore, denoting $k + \frac{R}{Z}$ by $\mu - 1$, the change in the deviation due to an angle of heel of 1° is

$$\left[\frac{Z}{\lambda H} (e - \mu + 1) \cos \zeta' - \frac{g}{\lambda} \cos^2\zeta'\right] \text{ degrees.}$$

The coefficient of $\cos \zeta'$ is called the heeling coefficient, and is denoted by J; therefore the change in the deviation due to an angle of heel of 1° is

$$\left[J \cos \zeta' - \frac{g}{\lambda} \cos^2 \zeta'\right] \text{degrees.}$$

291. The meaning of μ.—From § 267, if Z' is the total vertical force acting at the compass when the ship is upright, we have on the assumption that $h = 0$,

$$Z' = Z + R + kZ + gH \cos \zeta$$

and this is true whatever be the value of ζ. Therefore, if we suppose the ship to be headed successively in every direction from 0° to 360°, we have, since the mean value of the trigonometrical ratio on the right is zero

$$\begin{aligned} \text{mean value of } Z' &= Z + R + kZ \\ &= Z\left(1 + k + \frac{R}{Z}\right) \\ &= \mu Z. \end{aligned}$$

Therefore μ is the ratio of the mean vertical force at the compass at any place to the vertical force of the earth at that place, that is

$$\mu = \frac{\text{mean value of } Z'}{Z}.$$

292. The correction of the heeling coefficient J.—The expression, which has been found in § 290 for the change in the deviation due to an angle of heel of 1°, contains two coefficients, J and $-\frac{g}{\lambda}$. It is impracticable to counteract the force $-gH$, so that the correction of the deviation due to the heel is reduced to making $J=0$.

Now $$J = \frac{Z}{\lambda H}(e - \mu + 1)$$

and from § 287

$$1 + e = \lambda (1 - D').$$

Therefore $$J = \frac{Z}{\lambda H}\left[\lambda (1 - D') - \mu\right].$$

Therefore $$J = 0 \text{ if}$$
$$\mu = \lambda (1 - D')$$

that is, if

$$\frac{\text{mean value of } Z'}{Z} = \lambda (1 - D').$$

Therefore the mean vertical force at the compass must be so altered that its value becomes $\lambda (1 - D') Z$. If the spheres have been placed, and the altered values of λ and D' are λ_2 and D'_2

respectively, the mean vertical force at the compass must be altered to $\lambda_2(1 - D'_2)Z$.

293. The heeling error instrument.—In order to determine the number and positions of the vertical magnets required for the correction of the heeling error—that is, the amount of vertical permanent magnetism that must be added at the compass so that the mean vertical force may be $\lambda_2(1 - D'_2)Z$—an instrument called the heeling error instrument is employed, and one of these is supplied to each of H.M. Ships.

The heeling error instrument, Fig. 228, consists of a circular flat-sided brass case *aa*, provided with a stand *b*, and a chain *c* for suspending it when necessary. One of the sides is of glass and hinged at the bottom so as to form the door of the instrument, and on this glass door a horizontal diameter *dd* is marked.

Inside the case are brass bearers, capable of being raised or lowered by means of a lifter *e*, worked by a milled head at the back of the case. Above the bearers are agate planes, on which the knife-edges of the needle *NS* rest when the instrument is in use. A level *f* is provided, and so arranged that when the bubble is central the line *dd* is horizontal. The needle is round and graduated from the centre in a scale of equal parts, the North-seeking (red) end being denoted by a mark. The axis by which the needle is supported passes through its centre of gravity. Small aluminium rings or weights *w*, which fit closely on the needle, are supplied. The needle is kept in a special tin box when not in use. The needle, when mounted, should be kept raised above the agate planes by means of the lifter except when actually observing, and the greatest care should be taken to keep it free from rust and moisture.

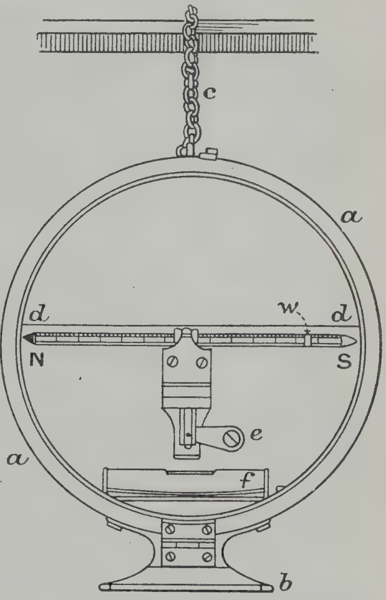


Fig. 228.

If the instrument is set up at a place free from local attraction, the needle, being placed in the plane of the magnetic meridian, will lie in the direction of the earth's total force at that place, so that the angle which it makes with the horizontal line *dd* is the dip at that place. Let one of the rings, of weight *w*, be placed on the upper end of the needle (the unmarked end in the Northern hemisphere), and so adjusted that the needle takes up a horizontal position, as indicated by parallelism to the line *dd*; then, if n be the number on the scale at which the inner edge of the ring is set, and Z the vertical force of the earth at the place, we have from Fig. 229

$$nw = lZ.$$

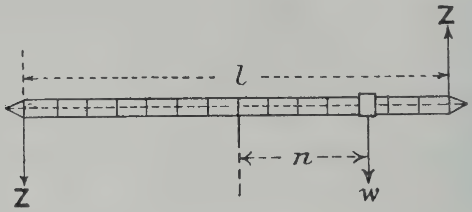


FIG. 229.

Similarly, if we take an observation at another place where the earth's vertical force is Z', we have

$$n'w = lZ'$$

Therefore

$$\frac{n'}{n} = \frac{Z'}{Z}.$$

294. The correction of heeling error in harbour.—The correction of the heeling error necessitates observations being taken on shore as well as on board.

Observations on shore.—The heeling error instrument should be taken on shore to a place free from local attraction and removed from possible magnetic influences. It should be set up on a stand or support so as to be at least 3 feet from the ground, and in such a position that the needle lies in the magnetic meridian. The needle should be levelled by means of one of the rings, and the value of n noted. Should one ring not be found sufficient, two rings in contact with one another, must be used, and the value of n read off from the inner edge of the inner ring; the reason for always reading from the inner edge of the ring is to ensure uniformity of observation.

Observations on board.—As stated above, it is impracticable to correct $\frac{g}{\lambda}\cos^2\zeta'$, and therefore, when correcting coefficient J, the ship's head should be East or West, because $\cos\zeta'$ vanishes at these positions. Since $\cos^2\zeta'$ is very small when the course is within 10° of East or West, any position of the ship's head within these limits is suitable, provided that the value of g is not very large.

Having removed the compass bowl place a wooden rod, of semicircular section, across the binnacle, in the direction of the magnetic meridian and with its flat side downwards. Pass the chain of the heeling error instrument over the rod, and raise or lower the instrument until the needle is in the same position as that lately occupied by the compass needles, and then secure the chain. Should the line *dd* not be exactly horizontal, it may be made so by moving the spare length of the chain to one side or the other as necessary.

From above, it is required to satisfy the equation

$$\frac{Z'}{Z} = \lambda_2(1 - D'_2);$$

that is

$$\frac{n'}{n} = \lambda_2(1 - D'_2)$$

or

$$n' = n\lambda_2(1 - D'_2).$$

The factor $\lambda_2(1 - D'_2)$ is called the heeling error constant, and its value, for each position at which a compass is placed in a particular ship, is given on a paper to be found in the box containing the heeling error instrument. The value of λ_2, which is the heeling error constant if D'_2 is assumed to be zero, is given in a pamphlet entitled "Spheres, Flinders Bar, etc." Therefore, the inner edge of the ring should be set at a scale division n', as found by multiplying n by the heeling error constant, and the needle should be placed in the instrument with its marked end towards the North.

If the North end of the needle dips vertical magnets should be placed in a specially constructed bucket below the compass, red ends uppermost, and raised or lowered as necessary till the needle is horizontal. If the South end dips the magnets should be placed with their blue ends uppermost. The distance between the top of the magnets and the compass needles may be read off on the marked chain which supports them.

On account of the possibility of magnetism being induced in the Flinders bar by these magnets it is advisable that they should be as low as possible, and therefore several magnets at a distance should be used in preference to a smaller number near to the compass.

In a Thomson compass (§ 300) another error, called the error of translation, exists, and this is due to the translation of the compass bowl arising from its mode of suspension. It has been found by experiment that this error is allowed for by lowering the bucket 2 inches after the correction has been made.

295. The correction of heeling error at sea.—It is obvious that, when correcting heeling error at sea, the value of n for the position of the ship cannot be obtained by observation. Now the value of n varies according to the vertical force of the earth, and therefore, if its value has been obtained at some place on shore, its value at the position of the ship may be deduced by aid of the chart of equal vertical force.

Example :—It is required to find the scale reading at which to set the ring of the heeling error instrument, in a ship in Lat. 30° S., Long. 0°, n having been observed at Portsmouth to be 30·0, and the heeling error constant for the compass being ·9.

From the chart of equal vertical force we have—

At Portsmouth - - - - $Z =$ ·425 dynes.
At the position of the ship - - $Z_2 = -$·250 „

Then, if n_2 is the value of n at the position of the ship

$$\frac{n_2}{n} = \frac{Z_2}{Z}$$

$$\therefore n_2 = 30 \times - \frac{\cdot 250}{\cdot 425}$$

$$\therefore n' = \cdot 9 n_2 = - \cdot 9 \times 30 \times \frac{\cdot 250}{\cdot 425} = - 15 \cdot 9.$$

The negative sign indicates that the ring should be placed on the North or marked end of the needle. The ring should, therefore, be placed on the marked end with its inner edge at the scale division 15·9.

At first sight the necessity for the correction of the heeling error may not be apparent, because a ship, unless she be a sailing vessel, does not heel to one side or the other for more than a few seconds; but, as a ship rolls, the vertical force which causes heeling error is applied alternately to starboard and port of the compass, and this periodic force on the compass needle causes the compass card to swing and become unsteady. Thus we see the necessity for the close correction of the heeling error, in order that the compass card may be steady under all circumstances.

296. The change of the heeling error due to change of magnetic latitude.—The heeling error, when corrected, will remain correct provided that the ship does not change her magnetic latitude, and this is so because, in the correction of this error, practical difficulties necessitate a departure from the main principle of compass adjustment—that is, of correcting like with like—and we correct the induction in soft iron, represented by $-e$ and $\pm k$ rods, by permanent magnets. Taking, as an example, the case of the compass of a ship built in England, we should probably have a $+R$, $+k$ and $-e$. These would all act in the same direction to cause heeling error, and permanent magnets, red ends uppermost, would have to be placed under the compass to counteract their effects. If the ship steams South, on arrival at the magnetic equator where $Z = 0$, k and $-e$ will have no effect, and fewer magnets will be required because R alone will be acting. When the ship arrives in the Southern hemisphere k and $-e$ will, after a time, counteract $+R$, and no magnets whatever will be required. Further South the effects of k and $-e$ may exceed the effect of $+R$, and magnets with their blue ends uppermost will be required.

Thus, after any considerable change of magnetic latitude, the heeling error should be re-corrected; but as, on each occasion of so doing, the vertical magnets are moved and possibly the magnetism induced in the Flinders bar or spheres altered thereby, it is necessary, whenever the heeling error is corrected, to obtain a new deviation table by observation.

From the formula it will be seen that the heeling error is a maximum when the ship's head is North or South; therefore, should the ship not be perfectly upright and the heeling error not exactly corrected, a change in the deviation for those directions of the ship's head may be expected.

CHAPTER XXVI.

THE MAGNETIC COMPASS—*continued.*

THE DESCRIPTION AND PRACTICAL CORRECTION OF THE COMPASS.

297. The bowl of the Chetwynd compass.—Magnetic compasses are of two kinds, according as the compass card lies in liquid or air. The two types of compasses in use in H.M. Ships are the Chetwynd compass and the Thomson compass, and as the former is in use in the majority of modern ships we shall describe it first.

A compass may be regarded as consisting of two parts, the bowl and the binnacle, each of which consists of a number of minor parts.

The upper part of the compass bowl, Fig. 230, consists of a brass cylinder $ABB'A'$, closed at the top and bottom by two flat glass discs AA' and BB'; in the centre of the latter is situated the pivot D. The cylinder is filled with pure distilled water in which there is 50 per cent. of alcohol to prevent freezing.

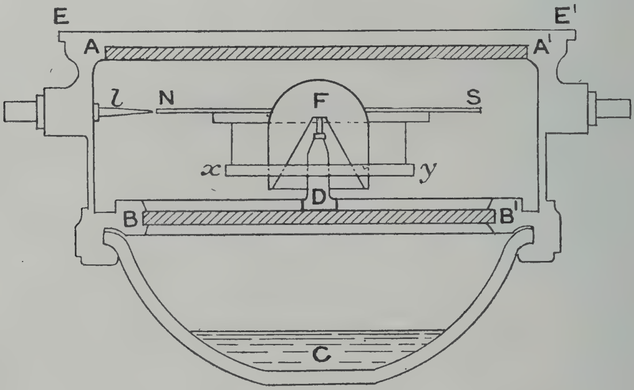


Fig. 230.

The card NS is of mica and is secured to a copper float F, in order to reduce the friction on the pivot D, and to a system of two magnets xy, each 3·75 inches long. The lubber's point l consists of a horizontal pointer projecting inwards from the brass cylinder, its extremity, reduced to a fine point, being close to the edge of the card. In order to allow for the expansion and contraction of the liquid and metal due to change of temperature, two small corrugated chambers *g*, Fig. 231, called expansion chambers, are fitted, one on either side of the bowl. These chambers are in communication, by means of a small hole *h*, with the interior of the bowl, and are consequently full of liquid. The corrugated sides of these chambers yield to the expansion and contraction of the liquid and bowl. On the side of the bowl is a hole for adding to the liquid in the bowl as necessary; it is called the filling hole and is fitted with a screw plug and leather washer.

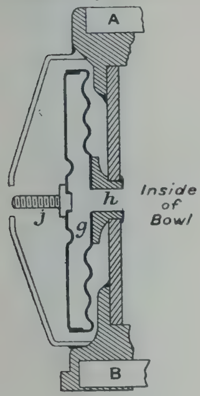


FIG. 231.

Attached to the lower portion of the bowl is a glass chamber *BCB′*, Fig. 230, which is partially filled with castor oil or glycerine; this gives stability to the bowl in a seaway, and at night diffuses the light placed beneath the bowl.

In the latest pattern the glass chamber *BCB′* is absent and a ring is fitted to give stability to the bowl.

The bowl is supported by gimbals on roller bearings, the outer gimbal ring being pivoted in roller brackets on the side of the binnacle.

The metal ring *EE′*, called the verge ring, which secures the upper glass of the bowl in place, is, in the standard compass, graduated in degrees from 0° to 180° to starboard and port, the graduation 0 corresponding to the ship's head. This is useful because, when a bearing of an object is taken, a small pointer on the azimuth mirror indicates the angle on the bow. In steering compasses the verge ring is fitted with an adjustable magnifying prism over the lubber's point, to enable the steersman to more clearly see the direction of the ship's head; counterpoise weights are fitted on the opposite side of the verge ring.

298. To remove a bubble from the compass.—If air enters the compass bowl a bubble is formed which lies between the upper glass and the compass card. This not only makes the reading of the graduations of the card difficult but reduces the sensitiveness of the card and causes it to hang.

To remove a bubble, the bowl should be unshipped from the binnacle and laid on its side with the filling hole uppermost. The screw plug should first be removed from the filling hole, and then the expansion chambers distended to their maximum extent; this is done by aid of small milled nuts which screw on to the screw *j* (Fig. 231), they will be found in the box in which the compass is supplied. Care should be taken not to strain the expansion chambers when distending them. This action of distending the expansion chamber causes the level of the liquid to fall. Recently distilled water should then be poured into the filling hole, the bowl being gently moved from side to side in order to facilitate the escape of the air. When it is considered that all the air has escaped, the milled nuts on the expansion chambers should be eased back one or two turns, so as to allow the expansion chambers to slightly close; the extra pressure thus brought on the liquid will cause a slight overflow at the filling hole, and should tend to drive out any air that remains. The plug of the filling hole should then be screwed in, care being taken that the leather washer is in place; the milled nuts may now be eased up and removed. Should there still be an air-bubble the operation should be repeated.

299. The binnacle.—The binnacle, Fig. 232, consists of a hollow wooden stand at the top of which are fittings for carrying the bowl, while outside and inside it are various arrangements for carrying and securing the different correctors. Screwed to the outside of the binnacle is the brass case for the Flinders bar, and on either side are brass brackets, *c*, *c*, to which the spheres are secured. On the opposite side to the brass case are situated doors by which the inside of the binnacle can be reached. Inside are brass tubes for carrying and securing the fore-and-aft and athwartship permanent magnets. There are two sets of tubes, *a* and *a*, for carrying the fore-and-aft magnets, but only one set, *a′*, for the athwartship magnets, and this is situated on the side of the binnacle opposite to the brass case.

The brass tubes are attached to endless chains, *b*, *b*, and so arranged that, by turning a handle, their distances from the compass needles can be varied at will. The mechanism is securely locked by two studs, *d*, *d*, when the safety door *g* is closed.

Along the centre line of the binnacle is a brass tube, *e e*, in which is a bucket, *f*, for carrying the vertical magnets. The bucket is supported by a chain *h*, each link of which measures half-an-inch, in order that it may be lowered or raised as required; the number printed on that link of the chain, which is at the securing position, indicates the distance in inches between the upper ends of the magnets and the compass needles.

At the upper part of the binnacle are two brass doors which open into a space immediately below the compass bowl; in this space there is an electric lamp and a contrivance for regulating the illumination of the compass. If necessary the doors may be removed and oil lamps substituted.

On the top of the binnacle is fitted a removable brass helmet which completely covers the compass bowl, and is conveniently fitted with sliding shutters and windows through which observations can be made.

The binnacle is secured to the deck by four bolts, and care should be taken that it is so secured that the line joining the

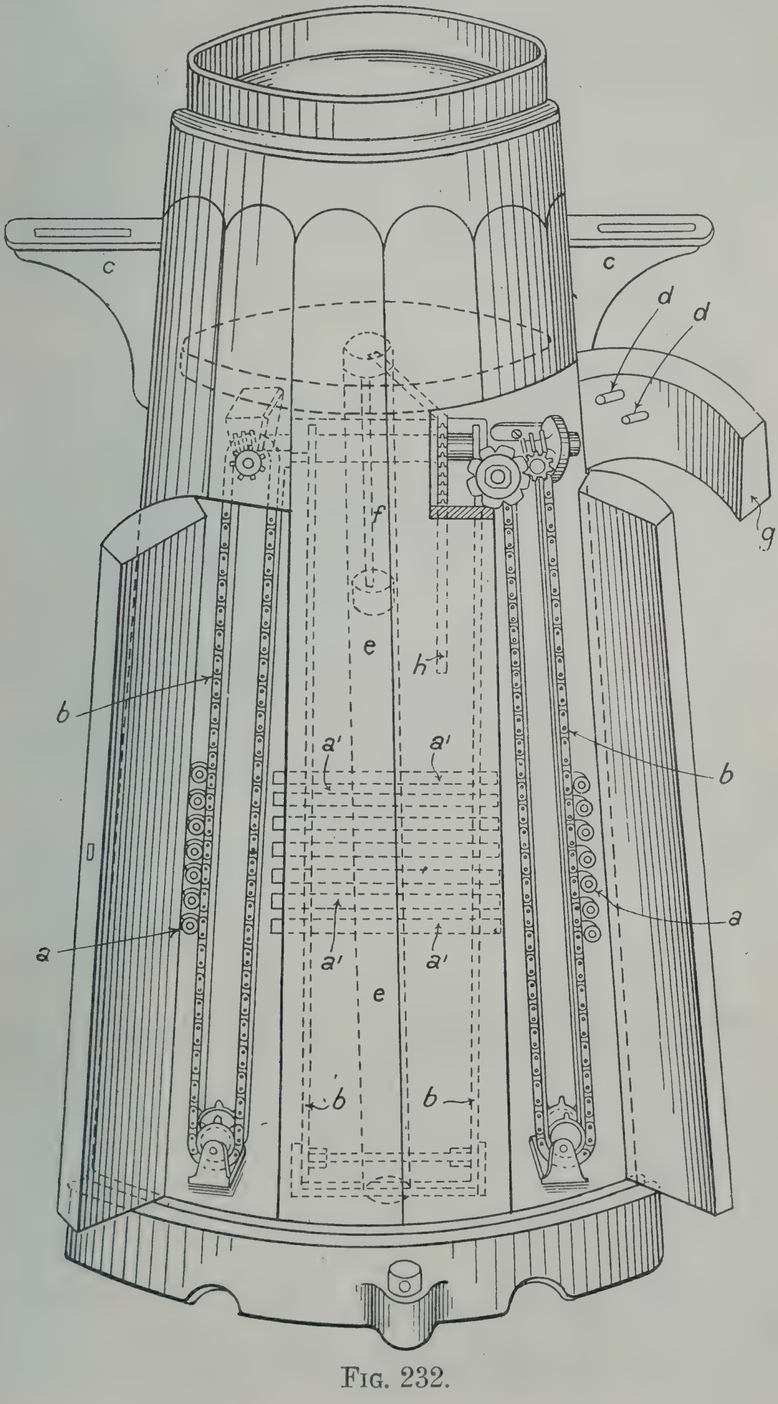


Fig. 232.

centre of the compass card to the lubber's point is parallel to the fore-and-aft line of the ship To ascertain if this is so two plumb lines should be suspended, one before and one abaft the compass, from points whose positions in the fore-and-aft line have been found by measurement. A straight edge laid on the compass in the plane of the two plumb lines should pass vertically over the centre of the compass card and the lubber's point.

All material used in the construction of the binnacle is non-magnetic.

The doors of the binnacle which, when shut, secure the magnets in the tubes, should always be kept locked, in order that unauthorised persons may not be able to tamper with the magnets.

300. The Thomson compass.—This compass is in use in many of the older of H.M. ships; the card, which is very light, is pivoted in the centre of the bowl, and consists of an aluminium ring joined to an aluminium centre by thirty-two silk threads; a ring of paper on which are printed the graduations is cemented to the aluminium ring. The needles, which are very weakly magnetised, are suspended under the card by silk threads. The card is pivoted on a small brass rod having an iridium point.

This type of compass is very sensitive, but as the retarding influence of the liquid is absent, oscillations are liable to be set up by shocks, gunfire, and the motion of the ship.

The binnacle consists of a wooden stand with holes drilled in it to receive the magnets; it is fitted with brackets for the spheres, and a brass case for the Flinders bar as in the Chetwynd compass.

In a Thomson standard compass the verge-plate is graduated in a similar manner to that of a Chetwynd standard compass. In a Thomson steering compass no prism is fitted, but a magnifying glass, placed on the verge glass if desired, may be used instead.

301. The azimuth mirror.—The azimuth mirror, Fig. 233, is an instrument which may be placed on the top of the compass bowl for the purpose of taking bearings. It consists of a stand, on which is mounted a pedestal which carries a prism, magnifying glass, pointer, &c. The stand has three arms, the extremity of each of which is fitted with a clip, which engages over the projection of the verge ring of the compass, in order to guard against displacement by shock. From the centre of the bottom of the stand projects a small pin which enters a hole in the centre of the upper glass of the compass bowl. Above the stand is a pedestal at the lower extremity of which is a pointer *a a′* which lies, one end, *a*, over the graduation of the compass card and the other, *a′*, over the graduation of the verge-plate. On the pedestal is carried a magnifying glass, *b*, and a prism, *c*. The prism may be revolved about a horizontal axis by means of a milled head *d*, on which is engraved an arrow. Two coloured shades *e*, *e*, are provided for use when taking bearings of the sun, as well as a small level *f*. In the centre of the instrument is a socket, in which may be stood a vertical pin *g g*, called a shadow pin. The vertical plane which passes through the shadow pin *g g* and the pointer *a a′* cuts the prism at right angles; but, should it not do so, small clips are provided by means of which the prism may be adjusted.

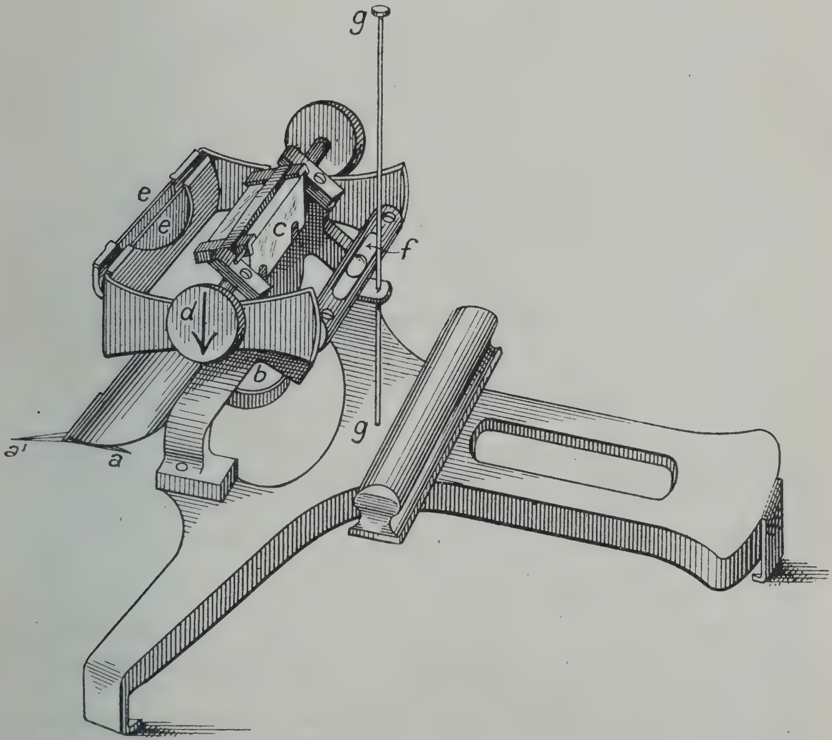
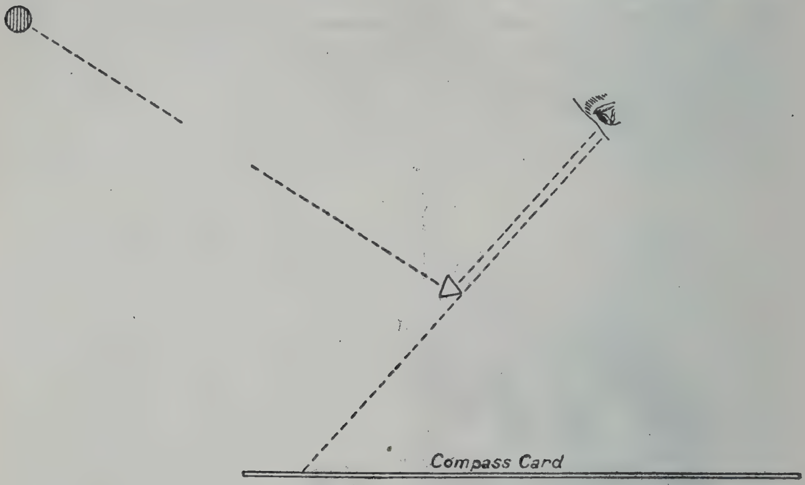


Fig. 233.

302. How to take bearings.—As stated above, the milled head for rotating the prism of the azimuth mirror has an arrow head engraved on it, and the direction of this arrow, whether pointing up or down, indicates the position of the prism according to which method of taking bearings is employed.

Arrow up.—This method is generally used when taking bearings of elevated objects, such as heavenly bodies, but, if desired, it may be used for objects on the horizon. Fig. 234 shows the position of the prism, the ray from the object being reflected upwards to the observer's eye which is in such a position that the graduation of the compass card is seen directly through the lens. A small movement of the prism will enable the object and the graduations of the compass card to be seen together with the small pointer at the base of the instrument, and the graduation which is coincident with the object may be read off.



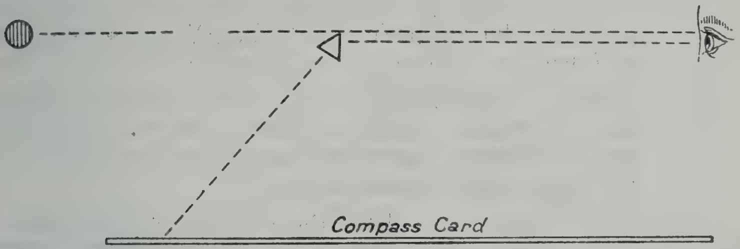
"ARROW UP"

FIG. 234.

Care should be taken that the reflection of the object is coincident with the pointer; when this is so the azimuth mirror is pointing directly at the object. The error in the bearing observed, due to lack of this precaution, is not very great provided that the altitude of the object is not greater than 38 degrees, but above that altitude the error increases very rapidly; for this reason, when great accuracy is required, it is inadvisable to take bearings of heavenly bodies whose altitudes exceed 38 degrees.

Arrow down.—This method is that most generally adopted when the object to be observed is on or near the horizon. Fig. 235 shows the ray from the object passing just over the centre of the prism to the observer's eye; at the same time the rays from the graduation of the compass card and from the small pointer are reflected in the same direction. The advantages of this method for general work are twofold: in the first place the azimuth mirror, when once set for a particular observer, does not need constantly adjusting, and this is an important matter when taking cross-bearings because it avoids delay between taking the bearings; in the second place, if the object is indistinct or difficult to distinguish from other objects, the operation is simplified because the object is seen directly and not by reflection.

When taking bearings the observer should be careful that the bowl is horizontal, as indicated by the small spirit-level on the azimuth mirror, and he should not be touching the azimuth mirror or compass bowl at the instant at which an observation is taken.



"ARROW DOWN"

FIG. 235.

It will be obvious from Figs. 234 and 235 that the bearings of an object taken by the two methods should agree; should they not do so the prism needs adjustment, and this may be effected by means of its securing screws.

Bearings may be taken without the aid of the azimuth mirror by means of the shadow pin which may, if desired, be stepped in a tripod carrier which is supplied with the azimuth mirror. The eye, shadow pin, and object are brought into line, and it is noted where the vertical plane through this imaginary line cuts the compass card. The degree of accuracy obtained by this method is not very great, but it is frequently useful in wet weather.

303. The bearing plate or Pelorus.—In some ships it is impossible to obtain an all-round view from the standard compass, and in such cases a bearing plate, which is merely a dummy compass set up near the standard compass, is of great assistance in taking bearings. It is also useful in a fleet for keeping station on a particular bearing from another ship, when it is inconvenient to use the standard compass.

A bearing plate consists of a circular brass plate with a raised rim, 4 inches in diameter, on which a lubber's point is marked. This plate is suspended on gimbals and weighted so as to remain horizontal when the ship rolls. The gimbal ring is mounted on brass supports fixed in a square wooden box. Inside the raised rim of the plate there is a disc, marked as a compass card and capable of rotation about its centre. Outside the raised rim is a recessed part for a movable brass circle, on which is mounted folding sight vanes fitted with shades and a reflecting glass. An arrow head is inside the reflector for reading off the bearing or setting the vane.

When using the bearing plate, the essential conditions are:—

(1) The lubber's point should be exactly in the fore-and-aft line of the ship.

(2) The plate should be horizontal.

(3) The degree shown on the compass engraved on the plate opposite the lubber's point should agree with the standard compass course of the ship.

(4) A "stop" should be given from the standard compass when the ship's head is exactly on her course, and the observer at the plate should note the bearing of the object at the same instant.

In short, it is necessary to have the dummy compass card or plate pointing in the same direction as the standard compass card, when the bearing by it will be the same as by the standard compass.

It is sometimes desirable to steady the ship on a particular magnetic course, and this may be done by means of the bearing plate as follows; find the magnetic bearing of a distant point from the chart, and set this and the required magnetic direction of the ship's head on the bearing plate. Turn the ship in azimuth until the distant point can be seen in the sight vanes; the ship's head will then be on the magnetic course required. If no distant point is available the operation can be effected at any particular instant by means of the azimuth of the sun or other heavenly body. Thus, suppose it is required to steady the ship on N. 50° W. (mag.), the magnetic bearing of the sun or distant point being N. 67° E. Set the dummy card to N. 50° W., opposite the lubber's point. Set the sight vanes to N. 67° E., and turn the ship in azimuth till the point or heavenly body can be seen in the sight vanes. The same method of putting a ship's head on a magnetic course can be practised, using the graduations on the verge plate of the standard compass.

304. The compass in a conning tower.—When a compass is situated in a conning tower, the iron of which is a better conductor than air, a large percentage of the earth's lines of force travel through the metal of the tower and emerge on the other side, and only a small percentage pass directly through the tower; these, combined with the lines of force due to the induced magnetism of the conning tower (§ 255), give to the compass its directive force. For this reason the value of λ at a compass so placed is generally small, and sometimes as low as ·2. On the ship's course being altered, the direction of the lines of force, due to the magnetism of the conning tower, moves slightly in the direction of the new course and gradually returns to the original direction (North and South). The result is that the deviation of a compass in a conning tower is not what may be expected immediately after a change of course, but gradually comes to its normal value after a more or less short interval. Therefore, when using a compass, so placed, for steering purposes, frequent checks should be made by means of the standard compass. It is found that the North point of the compass needle always moves slightly in the direction in which the course is altered, an effect which is frequently alluded to as sluggishness. To avoid this, in modern ships the compass is set up in a position at some distance below the conning tower, a light and system of lenses being employed to project an image of the compass card on to a suitable screen in the conning tower. Such a compass is called a projector compass and the position selected for it should be sufficiently far removed from dynamos, motors, &c., and such that λ has a good value there.

305. Precautions to be observed with regard to electrical instruments, &c.—As explained in § 256 a wire which carries an electric current is surrounded by a magnetic field, so that the electric lighting of a compass introduces a difficulty; but it is found that if the lead and return wires are clipped close together, the magnetic effects of one are counteracted by those of the other. The following table gives the distances from a compass within which the instruments mentioned should not be brought :—

Instrument.	From Standard Compass Position.	From Lower Conning Tower Position.
	Feet.	Feet.
Alternator, Turret danger signal, 220 volt, automatic starter for (Kilroy).	12	16
Alternator, Turret danger signal, 220 volts (Kilroy)	20	28
Ammeter, ammunition hoist - - - - - -	4	4
Bell, 15 volt - - - - - - - - - -	4	4
Breaker, Branch (Whipp and Bourne) - - -	9	13
,, Main supply (Whipp and Bourne) - -	15	19
,, Circuit (Crompton) - - - - - -	10	14
,, ,, (Newett) - - - - -	4	6
,, ,, for torpedo dropping gear - -	5	8
Compass, Magnetic - - - - - - - -	4	4
Contactor, Branch, 809, 95 lbs. (Whipp and Bourne)	10	14
,, ,, No. 11, 45 lbs. (Whipp and Bourne)	4	4
Controller, Projector (Crompton) - - - - -	10	14
Distributor box, 220 volt, Patt. 588 - - -	6	9
Dynamo, 4 poles, 80 volt, 600 amperes - -	25	—
,, other types, 300 amperes and more - -	60	—
,, ,, ,, 400 ,, ,, ,, -	70	—
,, 200 K.W., 220 volt, 6 pole - - -	45	70
Fan, small high speed (Blackman) - - -	4	4
,, motor, 80 volt (Verity) - - - - - -	15	20
,, 100 volt, ½ ampere - - - - - -	4	4
,, 220 volt, 1 ampere - - - - - -	6	9
,, 7½ inch, 220 volt, 2 amperes (Siemen) - -	6	9
,, 12½ inch, two speeds - - - - - -	6	9
,, ,, (Westinghouse) - - - - -	9	13
,, 20 inch 220 volt, 2 amperes (Verity) - -	8	12

Instrument.	From Standard Compass Position.	From Lower Conning Tower Position.
	Feet.	Feet.
Fan, 35 inch (British, Thompson Houston)	16	23
Fire control, range receiver (Barr and Stroud)	5	8
,, ,, ,, for 4-inch guns	4	4
,, ,, ,, screened (Vickers)	7	9
,, ,, ,, unscreened (Vickers)	12	15
,, ,, transmitter (Barr and Stroud)	5	8
Forbes speed indicator, receiver	4	6
Gong, Captain's, Indicating shutter for	4	4
,, ,, Iron case for	4	4
,, Reply (Siemen)	6	9
,, other patterns	6	9
Gyro-compass, "Anschütz." Motor generators for	18	25
,, ,, ,, receivers	2	2
,, ,, ,, Reversible motor for	4	4
,, ,, "Sperry." Motor generator for	10	14
,, ,, ,, receivers	2	2
Hummer, Transformer box for	4	4
Indicator, Helm (Elliott Bros.)	4	6
,, ,, (Eversheds)	4	4
,, Revolution (Elliott Bros.)	4	4
,, ,, (Two) (Everett Edgcombe)	4	4
,, ,, ,, (Elliott Bros.)	4	4
Isolator, 60 volt, 8 amps. (Evershed and Vignolles)	10	14
Junction box, 220 volt, Patt. 586	11	15
Lamp, Arc, 100 volt, 5 amperes	10	14
,, Portable, 16 c.p., with iron protected screen	4	4
,, Projector compass, 6 volt	—	Nil
,, ,, ,, 220 volt, 150 c.p.	(No effect in position as fitted.)	
	Inches.	
,, 16 c.p.	7	
	Feet.	Feet.
Motor, Ammunition hoist for 6-inch guns	12	—
,, Bakery, 220 volt (Lawrence Scott)	4	4
,, Reversible, for gyro-compass (Elliott Bros.)	4	4
,, Brine pump	7	10
,, Capstan, Multipolar, 50 h.p.	30	—
,, Coal hoist, 220 volt, 17 h.p. (Siemen)	10	14
,, Compressor, CO_2	12	16
,, Dotter, 220 volt	8	11
,, Dredger ammunition hoist (Armstrong Whitworth).	10	14
,, Flue cleaning, 80 volt, 20 amperes	9	12
,, generator:—		
,, Fire control	10	14
,, ("Hibernia" class)	12	16
,, Navyphone	12	20
,, Searchlight (Mather and Platt)	14	20
,, ,, 220 volt (Laurence Scott)	24	36
,, ,, ,, (Westinghouse)	13	17
,, Telephone (Laurence Scott)	22	30
,, lift (Lawrence Scott)	8	12
,, Oil pump	9	13
,, pump, 10-ton (Verity)	11	16
,, ,, 50- ,, (Laurence Scott)	13	19
,, saw bench, 80 volt	13	18
,, sounding machine, 220 volt (Kelvin)	4	4

Instrument.	From Standard Compass Position.	From Lower Conning Tower Position.
	Feet.	Feet.
Motor, Torpedo bar, 220 volt, 39 amperes (Verity)	28	42
,, Training searchlight (Crompton)	5	7
,, Turbine turning, 220 volt (Allen)	24	36
,, Workshop, 220 volt, 7½ h.p. (Newton)	10	14
Regulator, Shunt—For telephone motor generator	4	4
Resistance potentiometer, 100 volt (Kelvin)	4	6
,, ,, 200 ,, ,,	4	6
Seachlight, single projector	12	—
,, twin projector (Crompton)	12	—
Section box, Patt. 587	8	12
Starter, Automatic—For searchlight generator	10	14
,, CO_2 compressor motor	10	14
,, Searchlight motor generator	24	36
,, ,, ,, ,, (Westinghouse)	4	4
,, Shunt—For brine pump (Lawrence Scott)	12	16
,, Telephone motor generator	14	18
,, Workshop motor (Newton)	4	4
Telephone, Box, line coil	5	8
,, Patt. 2461 Navyphone	4	4
,, ,, 2462 ,,	4	4
Voltmeter, Patt. 2381	4	4
,, (Weston)	4	4
Wire, Main conducting	9	—
Wireless instruments:—		
Alternator, 100 volt, 24 h.p (Crompton)	13	20
,, Type 9, 100 volt	4	6
,, ,, 10	5	7
Auto transformer, converter for	6	9
Blower (Crompton)	6	9
Coil Impedence, Type 2, 80 volt	4	6
Combined starter and regulator, converter for (Crompton).	6	9
Induction coil	30	—
Key Magnetic, Patt. 461	6	9
Rotary converter, Type 2, 100 volt	4	6
Rotary converter (Crompton) for T.B.D.'s and small ships.	6	9
Rotary converter old type—For T.B.D.'s.	20	30
Fan, circulating	4	4
Set, battleship, auxiliary	4	6
,, cruiser, auxiliary, Type 9	6	9
,, Mark II. (for big ships)	12	18
,, submarine	—	6
Starter and regulator (Crompton)	18	24
Switch operating, Type 1, Patt. 1066	6	8
,, Relay, Type 1, Patt. 441	4	5
Transformer—For T.B.D.'s	4	4

These distances have been obtained by experiment for a standard compass position where $\lambda = \cdot 86$, and for a lower conning tower position where $\lambda = \cdot 65$.

In the construction of a ship, the following points, in addition to the distances given above, should be adhered to.

No iron or steel of any kind should be placed within 10 feet of the standard compass. The extremities of elongated masses of iron, or steel, should be placed as far as possible from the compasses. The nearest great funnel should not be nearer than 32 feet, and other iron or steel fittings of considerable dimensions, such as conning towers or turrets, should not be less than 20 feet from the compass.

No iron subject to occasional movement (such as revolving cowls, hatches, doors, &c.) should be fitted so near the compass as to disturb it. Any cowl which exceeds 6 feet in diameter, the nearest part of which, when turned in any direction, comes within 18 feet of the compass, should be made of non-magnetic material. In no case should iron or steel, subject to occasional movement, be fitted within 12 feet of a compass.

As regards the compass in the lower conning tower, no moveable iron or steel should be within 12 feet of the compass, and no fixed iron or steel, other than decks or bulkheads, within 10 feet. Bulkheads which are situated within 4 feet of the compass should be made of non-magnetic material, to a distance of 10 feet in the horizontal plane and 4 feet in the vertical plane from the compass, and doors, hatches, &c. within 12 feet of the compass, should be made of non-magnetic material.

In some vessels the davits, when turned in, have the effect of altering the deviation. The King's Regulations and Admiralty Instructions lay down that if the davits, when turned in, approach within 14 feet of the compass, the deviations are to be obtained by swinging the ship both with the davits turned in and out.

306. To obtain the deviation by observation.—The principle underlying the correction of the compass is to ascertain from analysis the forces which cause deviation—whether from the permanent magnetism of hard iron or induced magnetism in soft iron or from both, and then to apply correctors which produce equal forces in opposite directions. As we have seen in the previous chapter, the forces which cause deviation are involved in the coefficients, and to find these it is necessary to know the deviations for various directions of the ship's head (§§ 277, 278).

The difference between the magnetic and compass bearings of an object is the deviation, so that, to obtain the deviation of the compass for any particular direction of the ship's head, it is necessary to take the compass bearing of some object whose magnetic bearing is known or can be obtained. There are three methods in use for obtaining the deviation, namely :—

(*a*) By reciprocal bearings.
(*b*) By bearings of a distant object.
(*c*) By bearings of a heavenly body.
(*d*) By bearings of marks when in transit.

(*a*) *By reciprocal bearings.*—If the bearing of the standard compass is observed with a compass on shore which is unaffected by local attraction, the bearing so obtained is the magnetic bearing of the standard compass from the shore compass, and if reversed is the magnetic bearing of the shore compass from the standard compass, or what is called the reciprocal bearing. If, at the same instant, the bearing of the shore compass, as indicated by the standard compass, is observed, the deviation, for the direction of the ship's head at the instant, can be obtained. This method has certain advantages over the methods (*b*) and (*c*);

(1) The magnetic bearing and thus the deviation is immediately obtained.

(2) The ship may be under way, and may, if required, be actually steaming ahead while the observations are being taken. This greatly facilitates keeping the ship's head in any required direction.

(3) The ship may be comparatively close to the shore compass, while the method (*b*) necessitates the ship being at a considerable distance. Consequently this method can frequently be employed in thick or cloudy weather when the other two methods would be impracticable.

At many important ports, a bearing plate, fitted with sight vanes, is set up, so that its zero line is in the magnetic meridian of the place, and consequently bearings taken by it are magnetic. Such shore stations are provided with the means of signalling the results of observations to a ship, and are frequently made use of when adjusting compasses or swinging ship for deviation. If it is desired to employ this method at a place where no such provision exists, an improvised shore station may be set up by aid of the landing compass, care being taken, when selecting the position, that no local attraction or other magnetic influence is present.

In order that the observations, from the shore station and from the standard compass, may be simultaneous, it is necessary to have some prearranged code; the following signals are generally employed:—

A pennant at the mast-head "close up" signifies "Stand by."

The "dipping" of the pennant signifies "Observe."

A large flag should be suspended immediately above the standard compass in order to assist the observer on shore in taking the bearings.

When the observer at the standard compass is satisfied with his bearing he orders "dip," which signal is repeated at the shore station, and bearings are taken from both positions, that from the shore station being immediately signalled to the ship in order that the deviation may be noted at once.

(*b*) *By bearings of a distant object.*—With this method the compass bearing is taken of a well-defined object whose magnetic bearing is known; the difference between the two bearings is the deviation. The magnetic bearing is found—

(1) From the chart, as explained in § 307, provided it is seen that the survey was made in considerable detail (§ 169). On some charts of harbours there are lines which show the true bearing of a certain distant object, from which the magnetic bearing may be found. When making use of such lines, the position of the ship should be fixed, and the true bearing for the particular position of the ship can then be seen.

(2) By obtaining the horizontal angle between the sun and the object and at the same time noting the time by the deck watch; the true bearing of the sun may now be obtained, and the horizontal angle applied to this gives the true bearing of the object from which the magnetic bearing can be obtained.

(3) Approximately, from the mean of standard compass bearings on eight or sixteen equidistant points, provided that the circle, described by the standard compass, as the ship turns round, is small, and the object sufficiently distant.

In all cases when method (*b*) is employed the ship should be turned round in as small a circle as possible and it should be remembered that, provided the distance of the object is 350 times the radius of the circle, the magnetic bearing of the object will not differ by more than 10′ from the mean. If the distance of the object observed is less than the distance just stated, the magnetic bearing for each observation should be noted.

(*c*) *By bearings of a heavenly body.*—In this method the compass bearing of a heavenly body, the altitude of which is not greater than 38°, is observed; at the same instant the time by the deck watch is noted, in order that the true bearing may be obtained (§ 101) or taken from the Azimuth Tables or Azimuth Diagram; the difference between the true and compass bearings gives the compass error.

This method is most commonly employed when the ship is at sea, and, as will be explained in § 313, the mean of the compass errors on eight or sixteen equidistant points gives the variation at the place. The azimuth of the heavenly body which is selected should not be changing very rapidly, for, if it is doing so, a small error in the time produces a considerable error in the azimuth. The rate at which the azimuth is changing may be seen by inspection of the Azimuth Tables.

The azimuth of the sun at sunset or sunrise is given in the Azimuth Tables, so that if the bearing of the sun is taken when its lower limb appears to be about a semi-diameter above the sea horizon, the operation of finding the azimuth is simplified, because there is no necessity to find the hour angle. This does not apply to the moon, because, as explained in § 136, when the upper limb disappears, or appears, the true altitude of its centre is about 3′, and, therefore, when the true altitude of the moon's centre is zero, that is at moonrise or moonset, the moon is invisible.

(*d*) *By bearings of marks when in transit.*—When coasting and using a large scale chart, the survey for which was made in considerable detail, the deviation may be found by taking the bearing of two marks when in transit. The magnetic bearing of the marks may be found by drawing a line through them on the chart, and the comparison of this bearing with the compass bearing gives the deviation. The marks selected should be sensitive (§ 172), and no opportunity of employing such marks, for checking the deviation, should be allowed to pass.

307. To find the true bearing of an object by the Mercator's chart.—In Fig. 236 let *A* represent the position of an observer and *B* the position of a mountain peak on a Mercator's chart. Let the full curved line between *A* and *B* represent the arc of the great circle which joins these points, and the dotted line the circle of curvature of the curve at *A*. This circle may be regarded as coincident with the curve over the arc *AB*. Let *AN* be the tangent to the circle (or curve) at *A*, then the observer sees the mountain *B* in the direction *AN*, and the true bearing of the mountain is the angle *PAN*. Join *AB* and draw *BN* perpendicular to *AN* and let the angle *BAN* be denoted by θ, then the true bearing of *B* (*PAN*) is $PAB - \theta$. The angle *PAB* may be found by measurement from the chart, so that to find the true bearing we have to find θ which in all cases is a very small angle.

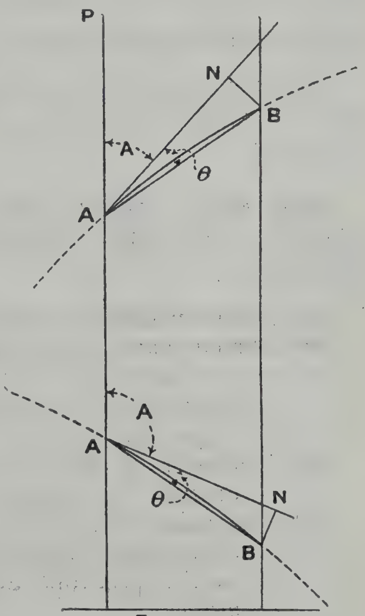


FIG. 236.

Now
$$\tan\theta = \frac{NB}{AN};$$
and neglecting small quantities of the second order,
$$AN^2 = 2\,NB\,.\,\rho\,,$$
where ρ is the radius of curvature of the curve which represents the great circle. Therefore
$$\tan\theta = \frac{AN}{2\rho}.$$

Now the radius of curvature of the curve which represents a great circle on the Mercator's chart is R cosec A cosec L, where R is the radius of the earth, A the bearing and L the latitude. Also $AN = g$ cosec A, where g is the difference of longitude between A and B.

Therefore

$$\tan\theta = \frac{g \operatorname{cosec} A}{2\,R \operatorname{cosec} A \operatorname{cosec} L};$$

$$\therefore\ \theta' \sin 1' = \frac{g}{2\,R \operatorname{cosec} L};$$

and since $\sin 1' = \frac{1}{R}$

$$\theta' = \frac{g}{2}\sin L;$$

Therefore the true bearing is found by measuring the angle PAB, and subtracting from it $\frac{g}{2}\sin L$ minutes.

It will be seen that unless the *d* Long. is great, or the latitude high, or both, θ will be very small and may generally be neglected.

308. The adjustment of compasses.—Before proceeding to adjust the compasses the following points should be attended to:—

(1) The ship should be upright.
(2) The caps and pivots should be in good order. This may be ascertained by deflecting the card one or two degrees, and noting whether it returns exactly to its original position.
(3) It should be ascertained whether the lubber's point is exactly fore-and-aft.
(4) The azimuth mirror should be examined for error of adjustment; that is, bearings observed with the prism in the positions arrow up and arrow down should agree.
(5) Everything of iron or steel should be in the position it usually occupies when at sea.
(6) No other ship should be nearer than two cables.

These points having been attended to, the corrections should be made in the following order:—

(1) Quadrantal deviation by spheres.
(2) Semicircular deviation due to induced magnetism (represented by a *c* rod) by Flinders bar.
(3) Heeling error by vertical magnets.
(4) Semicircular deviation due to P and Q by fore-and-aft and athwartship permanent magnets.

The reasons for this order are as follows:—

(*a*) As the deviation of the compass changes rapidly on alteration of course on account of the quadrantal terms, it is important that the quadrantal deviation should be corrected as early as possible. This may usually be done in harbour before proceeding to sea to adjust the compasses, the value of D being known or estimated, and the size and position of the spheres ascertained from the table in the Admiralty Manual (§ 281).

The spheres partially correct the heeling error, so that they should be placed before the remainder of the heeling error is corrected (§ 292).

(*b*) The Flinders bar corrects that portion of the heeling error due to $c\,H$ and therefore should be placed before the remainder of the heeling error is corrected (§ 290).

(*c*) The heeling error should now be corrected, because otherwise the ship would have to be exactly upright when correcting the semicircular deviation on North and South.

The spheres and Flinders bar having been placed in position as explained in §§ 279 and 281, the heeling error should be corrected as explained in § 294, and this can generally be done while the ship is proceeding to the position where the adjustment is to be made. The semicircular deviation should be corrected as follows:—Steady the ship on some cardinal point, say North, observe and note the deviation, and then insert the athwartship magnets as explained in § 280. It will now be found that the ship's head is not exactly North by compass, so again steady the ship on North, repeat the observation and, if necessary, alter the magnets; and so on until the deviation on North is zero. The ship's head should now be placed on an adjacent cardinal point, East or West, and an adjustment with the fore-and-aft magnets made in a similar manner. The ship should now be turned round and the deviations noted on the four cardinal and four intercardinal points, when a rough analysis will show whether coefficient D is correct and whether the other coefficients have any appreciable value. Should it be found that coefficient D has any value, the spheres should be moved as explained in § 281, and any small adjustment of the horizontal magnets that may be necessary should be made, the ship being steadied on the cardinal points as required.

When adjusting compasses the correctors should be placed so as to satisfy the following conditions:—

(*a*) The athwartship vertical plane which passes through the centre of the compass needles should always pass through the centres of every fore-and-aft magnet.

(*b*) The fore-and-aft vertical plane which passes through the centre of the compass should always pass through the centre of every athwartship magnet.

(*c*) The line of intersection of the vertical, fore-and-aft, and athwartship planes should coincide with the centre line of the vertical magnets or system of magnets.

(*d*) The horizontal plane which passes through the centre of the compass needles should also pass through the centre of the soft iron spheres.

(*e*) The horizontal plane which passes through the centre of the compass needles should also pass through a point on the Flinders bar which is distant about one-twelfth of the length of the bar from its upper end.

(*f*) Horizontal magnets should not be brought closer to the compass needles than twice the length of the magnets.

309. To obtain the deviation of and to adjust a between-deck compass.—In the case of a between-deck compass from which direct observation for deviation cannot be made, it becomes necessary to obtain the deviation by comparing the direction of the ship's head, as shown by such a compass, with that shown by the standard compass which has previously been corrected. In order to determine whether the spheres at such a compass have been correctly placed, it is necessary to determine what the deviation is when the ship's head is on the intercardinal points as indicated by that particular compass. For this reason an observer is stationed at each between-deck compass; at the instant the ship's head is on a particular point by the standard compass, a signal is made by means of a syren or whistle, and the observer notes the direction of the ship's head as shown by the between-deck compass. By comparing the direction of the ship's head with that shown by the standard compass, the deviation of any between-deck compass can be obtained for the direction of the ship's head as shown by that compass. To find the deviation on the cardinal, and intercardinal points, it is necessary to plot the deviations for the observed directions of the ship's head, and to take from the curve the deviations required.

While it is desirable to keep the deviation of each compass a minimum, it is inadvisable to frequently change the positions of the correctors; the correctors should only be moved when it is certain that a permanent change in the ship's magnetism has taken place, and, on all occasions of so doing, the ship should be swung and a new deviation table deduced as follows.

310. Swinging ship for deviation.—Swinging ship for deviation consists in turning her slowly round, steadying her on various courses and observing the deviation on each course.

When the deviations are large the ship should be steadied on every point of the compass in succession, but when they are small it is sufficient to steady her on every other point. When she is steady on a point of the compass, as indicated by the lubber's point, the deviation is observed for that direction of the ship's head by any one of the methods given in § 306; at the same instant the signal mentioned in the preceding article is given, and the observers stationed at the other compasses note the directions of the ship's head as shown by those compasses respectively.

A ship while being swung should be steadied, on each point on which the deviation is observed, for a sufficient time to allow the sub-permanent magnetism, due to the last direction in which she was heading, to disappear. As a general rule a ship should be steadied for at least a minute before an observation is taken, and a neglect of this precaution will result in there being an apparent *A* on analysis of the deviation table, an error which is sometimes referred to as Gaussin error. In a steering compass, the deviation of which is obtained by comparison with the standard compass, an apparent *A* may sometimes be caused by a misplacement of the lubber's point.

When swinging ship and observing a heavenly body, it is advisable, in order to avoid delay, previously to tabulate, for intervals of about four minutes, the magnetic bearings and corresponding deck watch times for the period during which it is likely that the observations will be taken.

It may happen that, after an action, a ship's magnetism may become so altered as to necessitate a new deviation table being made out. In the event of it being impossible to employ either of the foreging methods, the following procedure may be adopted.

Let us suppose that a ship *X* has been in action, and that soon afterwards she meets with a ship *Y* which has not been in action, and the deviations of whose standard compass are known. The method of reciprocal bearings can be employed, the bearings signalled from *Y* to *X* being magnetic.

A somewhat similar procedure may be followed in the case of two ships, for neither of which is the deviations known. Let *X* and *Y* be two ships which have been in action, with the result that the deviations of their compasses have been changed and are unknown.

The senior ship *X* directs *Y* to steer a steady course, S. 40° W. by compass, say; *X* then heads North by compass and reciprocal bearings are taken as shown in Fig. 237.

If δ is the Easterly deviation of Y on S. 40° W., we have

Magnetic bearing of Y from X - N. $(23^\circ - \delta)$ W.
Compass ,, ,, - N. 31 W.

Deviation of X on North - $(8^\circ + \delta)$ E.

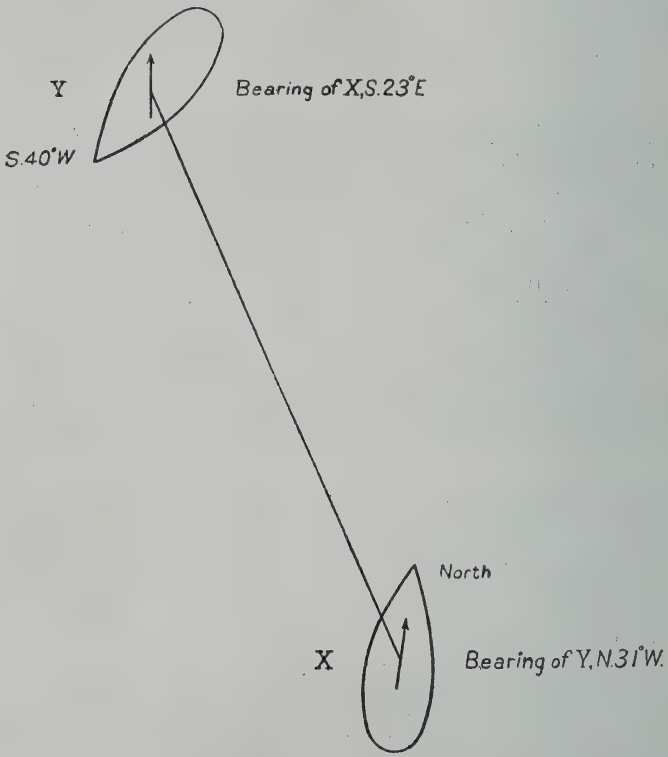


Fig. 237.

X now heads South by compass and reciprocal bearings are again taken as shown in Fig. 238.

In this case we have

Magnetic bearing of Y from X - N. $(68^\circ - \delta)$ W.
Compass ,, ,, - N. 56 W.

Deviation of X on South - $(12 - \delta)$ W.

Now from § 277, coefficient C for X is

$$\frac{\delta_N - \delta_S}{2} = \frac{(8^\circ + \delta) + (12^\circ - \delta)}{2}$$

$$= +10^\circ$$

Therefore, assuming that for X the coefficients A and E are zero, the deviation of X on North is 10° E.

Therefore

$$(8^\circ + \delta)\ \text{E.} = 10^\circ\ \text{E.}$$
$$\therefore\ \delta = 2^\circ\ \text{E.}$$

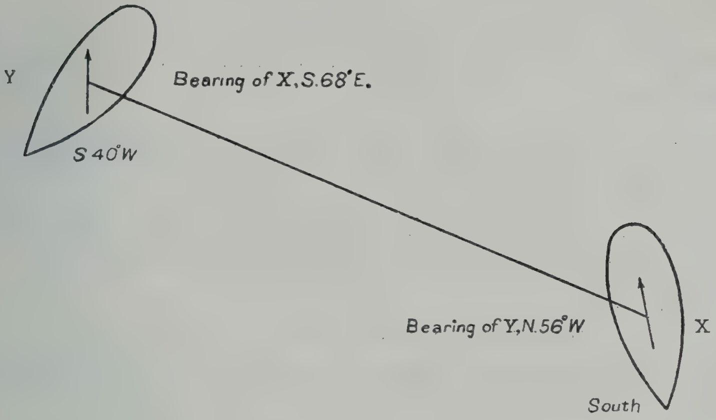


FIG. 238.

Having found the deviation of *Y* on S. 40° W., *X* may swing using the method of reciprocal bearings, and find the deviation on every point, care being taken that 2° E. is applied to each of the bearings signalled by *Y*.

311. Necessity for frequent observations for deviations.—When we reflect on the numerous forces mentioned in the previous chapters which tend to cause deviation, and that their effects vary in different ways as the course and the magnetic latitude vary, and if, further, we consider possible effects of the firing of guns, electric currents, movable stanchions, &c., it is clear that a deviation table is unlikely to remain correct for very long. Therefore the only safeguard against the ship being set out of her reckoning, due to an unknown error in the course steered, lies in frequent observation of the heavenly bodies, transit marks, &c., with which to check the deviation. Observations should be taken, when possible, on every change of course, or at least once a day, and the ship swung when necessary. It is often possible to obtain the deviation for a few directions of the ship's head, when time or opportunity is lacking for obtaining a complete swing, and no opportunity of so doing should ever be allowed to pass.

312. The criteria of a good deviation table.—To test the deviation table at a glance, the deviation on North should equal the deviation on South (with the sign changed), and the deviation on East should equal the deviation on West (with the sign changed), while the mean of the deviations on N.E. and S.W. should be equal to the mean of the deviations on S.E. and N.W. (with the sign changed). It should not be expected that the deviation table for a badly placed compass will satisfy these conditions, for it will be seen from § 277 that they are only strictly true when the coefficients A and E are zero.

A curve of the deviations shows whether any of the observations, from which the deviation table was constructed, were at fault.

313. Obtaining the variation by observation at sea.—Besides finding the variation from observations on shore, the variation may be found, and the chart kept up to date, from the analysis of the observations taken when the ship is swung for deviation, using the bearings of a heavenly body.

Now

$$\text{variation} = \text{compass error} \pm \text{deviation},$$

and if the deviations on eight or sixteen equidistant points are meaned (§ 277) the result is coefficient A. Therefore

$$\text{mean variation} = \text{mean of compass errors} \pm A.$$

Thus, if coefficient A for the compass is known, the variation at the place can be found.

As explained in § 310, when a ship is swung too rapidly, an error due to hysteresis, called Gaussin error, is introduced; this causes an apparent A which vitiates the variation, and its effect is felt to a small extent even when the swing is carried out quite slowly. For this reason, when swinging to obtain the variation, the ship should be swung in both directions, care being taken that the time occupied in swinging from point to point is about the same on both occasions; by this means the apparent A will probably be eliminated in the mean of the results. This apparent A is generally found to be + when swinging to port and − when swinging to starboard.

When forwarding results of swings to the Compass department of the Admiralty, care should be taken to give all necessary information as to the observations. The direction of each swing (starboard or port) should always be stated, for in the event of a swing having only been made in one direction, the observations may still be used for finding the variation, by employing an approximate value of the apparent A, as found from previous observations in the same ship.

CHAPTER XXVII.

THE GYRO-COMPASS.

314. Gyrostats and gyroscopes.—A solid of revolution which is capable of rotation about its axis is called a gyrostat, and the axis about which it rotates is called the axle of the gyrostat. The most important example of a gyrostat is the earth, which may be termed a natural gyrostat, its axle being the polar axis. Now, just as we were able to find direction by employing an artificial magnet or magnets, in conjuction with the natural magnet, the earth, so we can find direction by employing an artificial gyrostat, or gyrostats, in conjunction with the natural gyrostat, the earth. On account of gravity it is impossible to have a free gyrostat on the earth's surface, and, therefore, gyrostats are mounted in frames, when they are referred to as gyroscopes, a form of which is shown in Fig. 240.

In this chapter, the rotating wheel of a gyroscope will be referred to as the rotor, and the axle of the wheel will be referred to as the axle.

It will be found that, if a considerable spin is communicated to a rotor, the axle will endeavour to maintain the same direction in space, and will offer considerable resistance to being deflected from that direction, but, when forcibly deflected, the axle will move in a particular direction with regard to the axis of the applied couple.

315. The effect of a couple on a gyrostat.—A familiar example of the effect of a couple on a gyrostat is the case of a hoop bowled along the ground. So long as the plane of the hoop is vertical, no couple is acting, and the centre moves in a straight line, the axle of the hoop remaining parallel to itself. If, however, the plane of the hoop is inclined to the vertical, say to the left as viewed from behind, a couple is introduced, as shown in Fig. 239, due to gravity and to the reaction of the ground, and this tends to turn the axle of the hoop in the direction shown by the arrow. The result is that the hoop curves to the left, tending to make its direction of revolution the same as that shown by the arrow. This movement of the axle of a gyrostat is called precession, and the law of precession as enunciated by Foucault is "*every free rotating body, when*

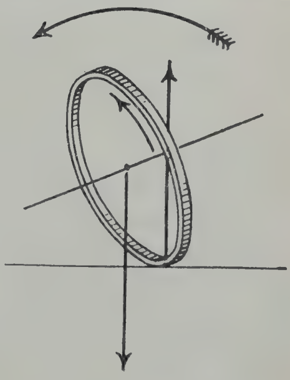


Fig. 239.

subjected to some other or new turning force, tends to set its axis of rotation parallel to the new axis of rotation by the shortest path, so that the two rotations take place in the same direction." This law may be illustrated by the following experiment.

Let the rotor (Fig. 240) be rotating in the direction shown by the arrow, and let a weight be attached to the frame at the point *A*, then a couple is introduced which is shown by the arrows *P*, *P*, and this couple tends to rotate the axle about

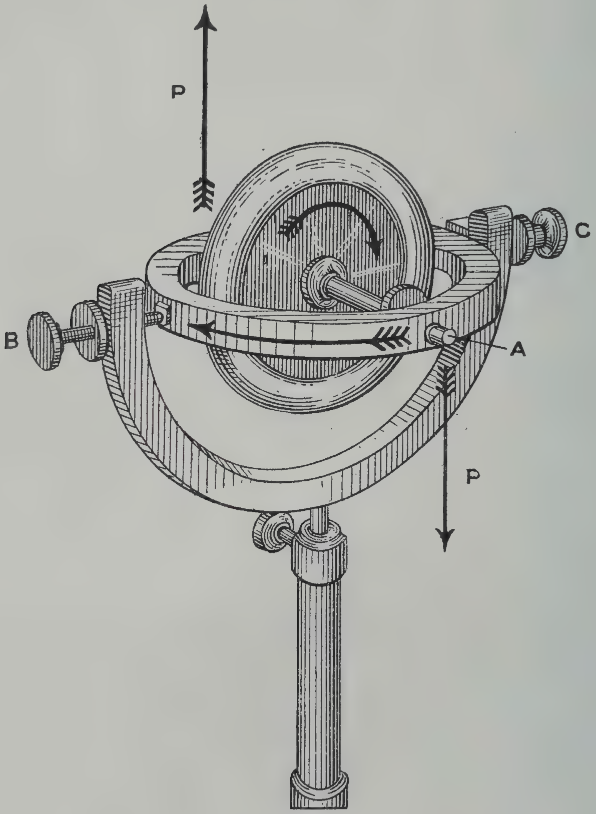


FIG. 240.

the axis *B C*. From Foucault's law we see that the rotor will precess in the direction shown by the arrow on the frame, in order that it may tend to set its axle so that the direction of rotation is the same as that of the couple. The rotor will continue to precess as long as the couple is applied. The effect of a couple is, therefore, to make the axle of the rotor precess in the plane which contains the axle and the axis of the couple.

316. The effect of the earth's rotation on a gyroscope.—At a particular instant let one end of the axle of the rotor shown in Fig. 240 be pointed to the North point of the horizon. We may imagine that the North point of the horizon at this instant coincides with a star *X*. Since the axle maintains the same direction in space, it always points to *X* notwithstanding the movement in space of the whole gyroscope due to the rotation of the earth.

Now, if we regard the earth as fixed, the star *X* appears to trace a circle on the celestial concave, and its altitude and azimuth continually change throughout the day; consequently, the axle traces out a cone, and the elevation of the end of the axle, and the horizontal direction in which it points, change with the changes in the altitude and azimuth of *X*. If we name the azimuth α and the altitude β, the curve which results from plotting α and β is as shown in Fig. 241, in which *N* is the North point of the horizon and *P* the North celestial pole.

If the end of the axle is directed to any other point of the heavens, the end of the axle, produced, traces a concentric circle on the celestial concave whose centre is the North celestial pole. If the end of the axle is directed to the North celestial pole, the circle reduces to a point and there is no motion of the axle whatever relative to the earth.

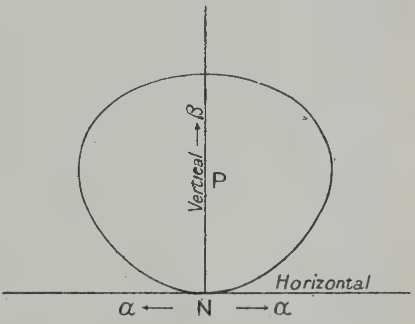


Fig. 241.

317. The effect of the earth's rotation on a gyroscope suspended from a point above its centre of gravity.—Let us again consider that the end of the axle, at a particular instant, is directed to the North point of the horizon; Fig. 242, which is on the plane of the horizon, shows by a dotted circle the path of the imaginary star *X* (§ 316). As explained above, the end of the axle, if produced, traces out this circle on the celestial concave, and therefore, after an interval, would be directed to some point *X′* on this circle. At this instant, the end of the axle is directed to the Eastward of North, and is tilted upwards through an angle which is equal to the altitude of *X′*.

Now let us assume that the gyroscope is suspended from a point which is above its centre of gravity and that the direction of rotation of the rotor is the same as that of the earth. That end of the axle which was directed to the North point of the horizon will be referred to as the North end of the axle, and only the motion of this end will be considered. Due to the mode of suspension, the tilt of the axle introduces a gravity couple, which causes the North end of the axle to precess to the Westward. As the earth continues to rotate, the angle of tilt increases, and consequently the velocity of precession increases, until a time arrives when the velocity of precession (to the Westward) is equal to that of the change of azimuth, due to the earth's rotation (to the Eastward), and consequently the North end of the axle moves no further to the Eastward. As the tilt, and consequently the velocity of precession (to the Westward) continues to increase, the latter become greater than the velocity in azimuth, and the North end of the axle commences to move to the Westward, and crosses the meridian at a considerable tilt.

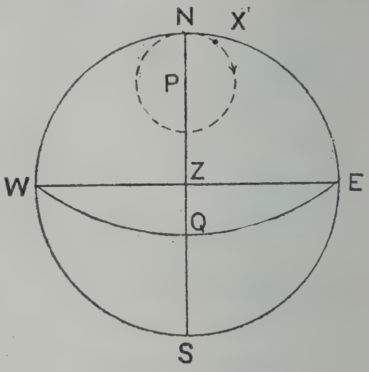


Fig. 242.

As soon as the North end of the axle is to the Westward of North, the tilt commences to decrease owing to the rotation of the earth, and consequently the velocity of precession (to the Westward) decreases. A time, will therefore arrive, when the velocity of precession (to the Westward) is again equal to that of the change of azimuth (to the Eastward), when the North end of the axle will move no further to the Westward. Later the velocity in azimuth becomes the greater, and the North end of the axle again moves to the Eastward and passes through the North point of the horizon.

If α and β are plotted, as in § 316, the result is a very elongated ellipse, Fig. 243, which touches the horizontal line at N. The semi-minor axis of the ellipse is very small, but in the figure the values of β have been magnified four times.

Had the North end of the axle been directed to any other point of the heavens, it would have traced out a similar ellipse, larger or smaller, whose centre would have been coincident with Y, the centre of the ellipse described above. Had the North end of the axle been originally directed to Y, the ellipse would have reduced to a point, and there would have been no motion of the axle whatever.

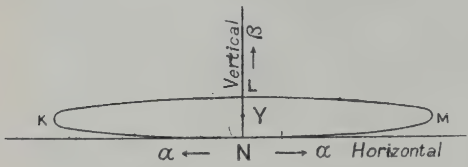


Fig. 243.

The time of a complete oscillation of the North end of the axle depends on the distance, between the centre of gravity of the gyroscope and the point of suspension, and on the velocity of the rotor. These are so arranged in the two types of gyrocompasses which are described in this chapter, that the time of oscillation is about 85 minutes, which is the same as the period of a simple pendulum, the length of which is equal to the radius of the earth.

The North end of the axle of any rotor may be easily distinguished, as it is that from which the rotor is seen to turn in an anti-clockwise direction.

318. The damping of the oscillations of a gyroscope.—It has been explained that the North end of the axle, except when directed to Y, must be in continual motion. Now the motion in azimuth would render such a gyroscope useless as a compass, and therefore it is necessary to introduce some means of damping the oscillations. In order to reduce the amplitude of the oscillations, a couple must be applied to the rotor, in such a manner, as to tend to make the axle point nearer to Y, or to make it precess towards the centre of the elliptic orbit. This is effected by one of two methods, the first to be described being that adopted in the "Sperry" gyro-compass.

If a couple in the horizontal plane is applied to the rotor, a precession in the vertical plane is set up; if this couple is applied so that the vertical precession is upwards while the North end of the axle is tracing out the arc KNM (Fig. 243), and downwards while it is tracing out the arc MLK, the result is that the North end of the axle moves in a spiral curve, and finally comes to rest, directed to a point, which is not on the meridian, but has a very slight Easterly azimuth and a slight altitude. This point is called the resting position of the axle.

If the North end of the axle had originally been directed to the North point of the horizon, and if α and β are plotted as in the previous articles, the result is a spiral curve as shown in Fig. 244, where T is the resting position.

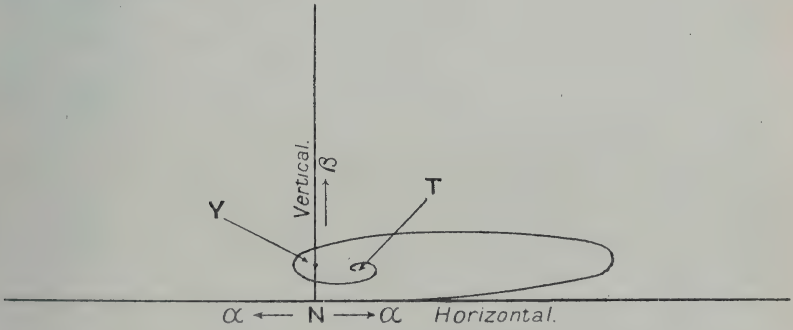


Fig. 244.

If the North end of the axle had been directed to any other point of the heavens, the result would be a curve of similar form, but in every case the resting position T would be the same.

The mechanical arrangements for the provision of this couple will be described in § 322.

The second method by which the oscillations may be damped is that employed in the "Anschütz" (three gyro) gyro-compass.

If a couple in a vertical plane is applied to the rotor, a precession in the horizontal plane is set up; if this couple is applied, so that the precession of the North end of the axle is to the Westward while the end of the axle is tracing out the arc *LKN* (Fig. 243), and to the Eastward while it is tracing out the arc *NML*, the result is that the North end of the axle moves in a spiral curve, and finally comes to rest directed to a point on the meridian which is not the North point of the horizon. This point is the resting position of the axle.

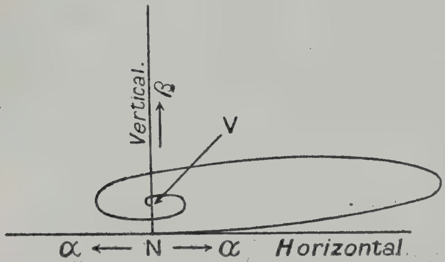


FIG. 245.

If the North end of the axle had originally been directed to the North point of the horizon, and if α and β are plotted as in the previous articles, the result is as shown in Fig. 245, where *V* is the resting position.

If the North end of the axle had been directed to any other point of the heavens, the result would be a curve of similar form, but in every case the resting position *V* would be the same.

The mechanical arrangements for the provision of this couple will be described in § 325.

319. The effect on a gyroscope when carried on board ship.—In the previous articles, the movement of the gyroscope in space was assumed to be due to the rotation of the earth alone, and therefore its direction of movement to be East. When the ship is steaming on any course, other than East or West, the direction of movement of the gyroscope in space is not East, but slightly to the North or South of it, according as the course is Northerly or Southerly. The ship's course and speed may be resolved into the speed in latitude (*V cos* course), and the speed in departure (*V sin* course), where *V* is the speed of the ship in knots. In Fig. 246, let *AC* represent the speed of the ship in the direction North or South, then *AC* represents the speed of the ship in latitude, *V cos* course. Let *AB* represent the speed of the ship in an Easterly direction, then *AB* represents the speed of the ship in space due to the rotation of the

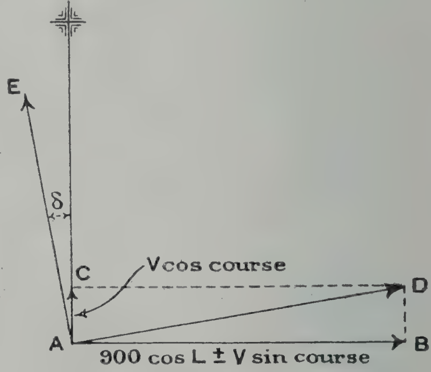


FIG. 246.

earth ± the speed of the ship relative to the earth; therefore, AB represents

$$(900 \; cos \; L \pm V \; sin \text{ course}) \text{ knots}$$

where L is the latitude of the ship. The resultant direction of movement of the gyroscope in space, is along the line AD, and therefore the axle lies along the line AE, which is perpendicular to AD. Let the deflection (CAE) of the North end of the axle be denoted by δ.

Now

$$\tan \delta = \frac{DB}{AB} = \frac{V \; cos \text{ course}}{900 \; cos \; L \pm V \; sin \text{ course}}$$

$$= \frac{V \; cos \text{ course}}{900 \; cos \; L} \text{ (nearly)}$$

$$\text{or } \delta^\circ = \tan^{-1} \frac{V \; cos \text{ course}}{900 \; cos \; L}$$

From this formula the deflection may be calculated for any given latitude, course and speed. It will be seen that the North end of the axle lies to the Westward of the meridian when the course is Northerly, and to the Eastward of the meridian when the course is Southerly.

This deflection δ is mechanically, and semi-automatically, allowed for in the "Sperry" gyro-compass. In the "Anschütz" gyro-compass, δ has to be applied to any course steered, or bearing taken, in the same way as the deviation of the magnetic compass.

320. The effects of the rolling and pitching of the ship on a gyroscope.—A gyroscope has great inertia in the vertical plane of the axle, which we may call the North South vertical plane, and cannot oscillate as a pendulum in this plane, without simultaneous oscillation taking place in the horizontal plane, due to precession; the period of oscillation in the North South vertical plane is, therefore, about 85 minutes (§ 317). In the East West vertical plane there is no gyroscopic effect, and the gyroscope may therefore oscillate in that plane as a simple pendulum. When a ship rolls and pitches, the gyroscope on board will oscillate in the East West vertical plane, due to the periodic impulses imparted to it by the motion of the ship, and the more nearly the periods of the ship, and of the gyroscope in the East West vertical plane, synchronise, the greater will be the amplitude of the oscillations.

When the ship's course is along or perpendicular to a meridian, the impulses due to rolling and pitching should have no effect on the gyroscope, because everything is symmetrical, and the impulses are alternating in direction. When a ship is steering on any other course, the impulses act unsymmetrically with regard to the East West vertical plane, and a horizontal couple is introduced, which increases or decreases the tilt of the axle, and consequently causes the North end of the axle to be deflected slightly from its resting position.

The direction of this deflection varies with the course, and the effect of pitching is opposite to that of rolling. The direction of the deflection under various conditions is as follows :—

Course N. Wly. or S. Ely.	Rolling.	Deflection	Westward.
,, ,,	Pitching.	,,	Eastward.
,, N. Ely. or S. Wly.	Rolling.	,,	,,
,, ,,	Pitching.	,,	Westward.

This deflection is not very great in the two types of gyro-compass described in this chapter, because they are so constructed, that the period of oscillation of the compass in the East West vertical plane does not synchronise with the average period of rolling or pitching of a ship. The possibility of the existence of this deflection must be borne in mind when the ship is in a sea way, as under certain circumstances it has been found to be as much as 5°. Experiments are now being carried out, with the object of determining a method for the elimination of this error.

321. Description of the "Sperry" gyro-compass.—

The "Sperry" gyro-compass consists of a stand or binnacle which supports a frame, which in turn, supports the sensitive element and card.

The frame *J*, Fig. 247, is pivoted in a gimbal ring *K*, by suitable bearings L_1, L_2 The ring *K* is pivoted in bearings L_3 in another ring, which is suspended by a large number of spiral springs from the upper edge of the binnacle. The rotor, driven by a three-phase stator, at about 8,600 revolutions per minute, rotates on a horizontal shaft *A*, within an airtight case *B*, from which the air has been partially exhausted by means of a small hand pump. The case *B* is pivoted on a horizontal axis *C*, which passes through its centre of gravity, and is supported in a vertical ring *D*.

The ring *D* is supported by a torsionless wire *E*, and mounted in bearings *F*, F_1, which allow a free oscillation, of limited amount, about the vertical axis within an outer ring *G*, called the phantom. The phantom has a hollow stem *H*, to which the strand *E* is attached at its upper end. The rotor and phantom are capable of turning in azimuth, with reference to the frame *J*, about the stem *H*.

Within the frame is mounted a follow-up motor *M*, which drives a gear wheel *N*; the gear wheel *N* is rigidly connected to the phantom *G*, and the motor *M* is driven through electric contacts on the ring *D*, in such a manner that every motion of the ring *D* in azimuth is immediately followed by an exactly similar motion of the phantom *G*. Thus we see, that any twist introduced in the wire strand *E*, by the motion of the rotor in azimuth, is instantaneously removed by the phantom *G*, which supports the upper end of the wire strand, making an exactly similar movement; this system provides an almost frictionless suspension. Gravitational stability is imparted to the rotor casing *B*, by a "bail-weight" *R*, which is pivoted on the phantom at *C*, and connected to *B* by means of a small pivot *S*.

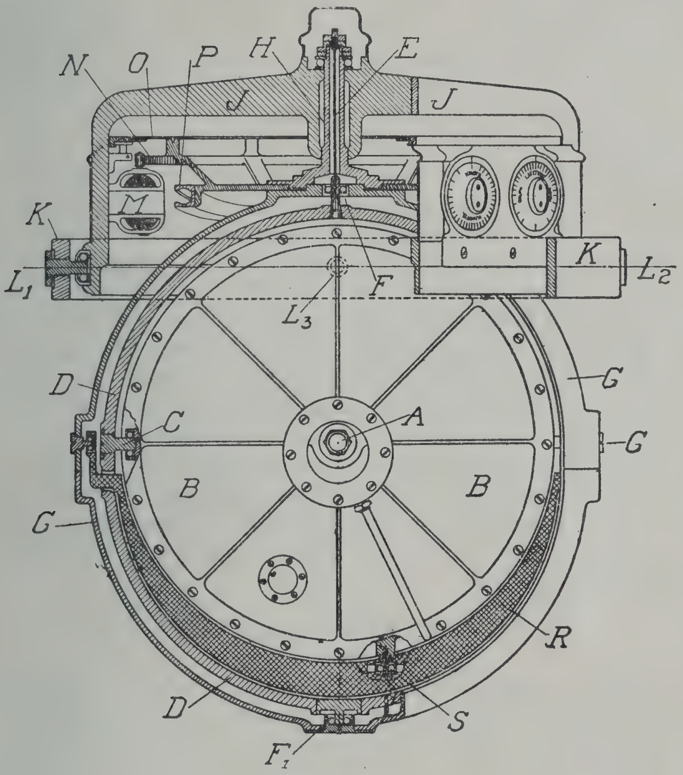


Fig. 247.

The compass card *O*, the graduations of which are the same as those of the magnetic compass, except that the degrees are marked from 0° to 359° clockwise from North, is secured to the phantom in such a manner that the North South line of the card is parallel to the axle *A*.

322. Damping of the oscillations of, and the automatic correction of the "Sperry" gyro-compass.—In order to introduce the horizontal couple necessary to provide the damping described in § 318, the pivot *S* (Fig. 247), connecting the heavy bail *R* to the rotor casing *B*, is placed slightly eccentrically, its distance from the vertical axis of the rotor being about $\frac{3}{8}$ inch. As the bail is pivoted at points which are above its centre of gravity, its natural tendency is to hang vertically downwards; when the axle is tilted, the pin *S* raises the bail from its normal position, and the eccentricity of the pin S causes the gravity couple on B to have a horizontal component, which provides the necessary vertical precession to reduce, or increase, the tilt; the instrument comes to rest with the North end of the axle directed to the point T of the celestial concave as described in § 318. This point T is slightly to the East of North and has a slight altitude, except when the instrument is on the equator; the deflection of the North point of the compass varies as the tangent of the latitude.

We have now to show how this deflection and that due to the ship's motion (§ 319) are allowed for. On the frame are two dials, one marked "Latitude" and the other "Knots," which should be set to the latitude and speed of the ship respectively. The setting of the latitude dial places the lubber's point at an angle r tan Lat. to the fore-and-aft line, where r is the number of degrees in the angle F_1AS. Attached to the phantom is a tilted grooved ring P; an arm, which is in connection with the mechanisms controlled by the two dials, works in the groove. When the ship alters course, the tilted ring rotates relative to the arm, which therefore moves up or down in the groove of the ring; the tilt of the ring is such that the vertical movement of the arm varies as the cosine of the course. The arm communicates its movement through the latitude and speed mechanisms to the lubber's point, and sets it at an angle δ to its normal position for the latitude. Thus the combined effect is that the lubber's point is set at an angle $\delta - \delta_2$ to the fore-and-aft line, where

$$\delta = \tan^{-1} \frac{V \cos \text{course}}{900 \cos \text{Lat.}} \text{ and } \delta_2 = r \tan \text{Lat.}$$

In order that the axle may be horizontal when no precession is taking place, an arrangement is provided for altering the centre of gravity of the bail, the centre of gravity being moved to the North when in North latitude and to the South when in South latitude. A level which is parallel to North South line of the card, is provided, and the position of the bubble indicates the angle of tilt of the axle; with experience the amount and direction of the deflection of the North point of the card from the meridian may be estimated from the position of the bubble. This is of considerable value, because after the rotor is first started, and has been precessing freely for a short time, the indication of the level may be taken as an approximate measure of the deflection, and the compass may be set by hand approximately on the meridian.

323. The "Sperry" receivers.—The alteration of the lubber's point, described above, would appear at first sight to only correct the compass for the course steered. Now the compass described above, called the master compass, is placed at some well protected position in the ship, in general in the lower conning tower, and in this position it is only used for

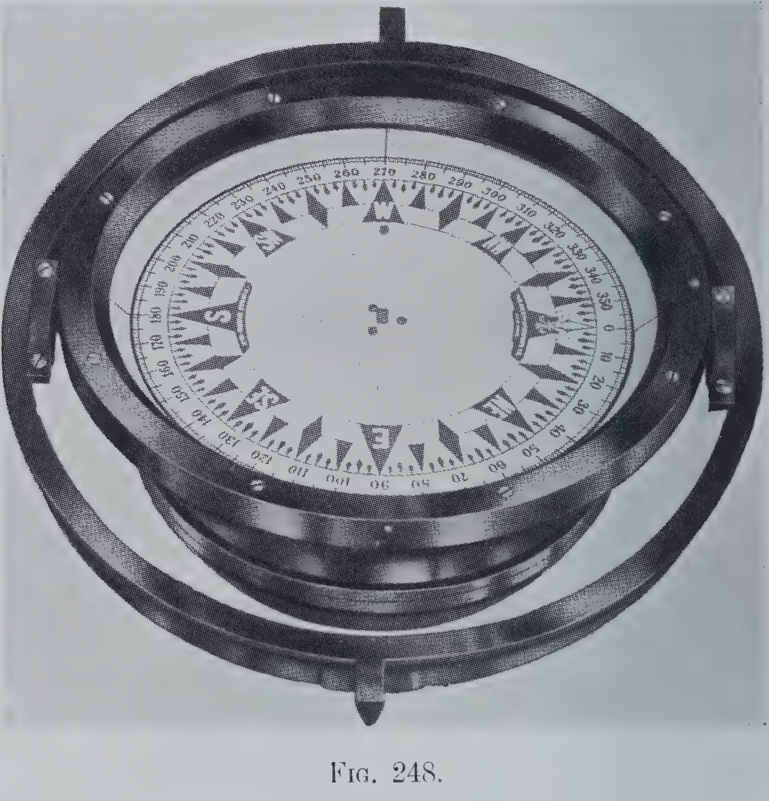


Fig. 248.

observing the direction of the ship's head. The movements of the master compass are conveyed electrically to instruments, called receivers, or repeating compasses, which are placed as convenient at different steering positions, and on the manœuvring platform. A "Sperry" receiver is illustrated in Fig. 248. The card is driven through gearing by an electric motor, and the instrument may be mounted in any position, but it is generally mounted vertically on a bulkhead, or horizontally in gimbals in a pedestal. When mounted on a manœuvring platform, it is supported in gimbals, and is fitted with an azimuth mirror, very similar to that described in § 301. The graduation of the card, opposite to the lubber's point of the receiver, is always the same as that opposite to the lubber's point of the master compass; as the necessary corrections are applied by moving the lubber's point of the master compass, the direction of the ship's head, as indicated by the receiver, is true. If the receiver is mounted in gimbals, so that it is horizontal, and if its lubber's point is in the fore-and-aft line, directions shown by it will be true.

When laying off courses, or lines of bearing, obtained from observations with this compass, it is convenient to lay them off from the outer graduated circle of the compass rose engraved on the chart, because this is graduated in the same manner as the compass card.

324. Description of the Anschütz (three gyro) gyro-compass.—The Anschütz (three gyro) gyro-compass consists of a metal stand or binnacle which supports a frame-

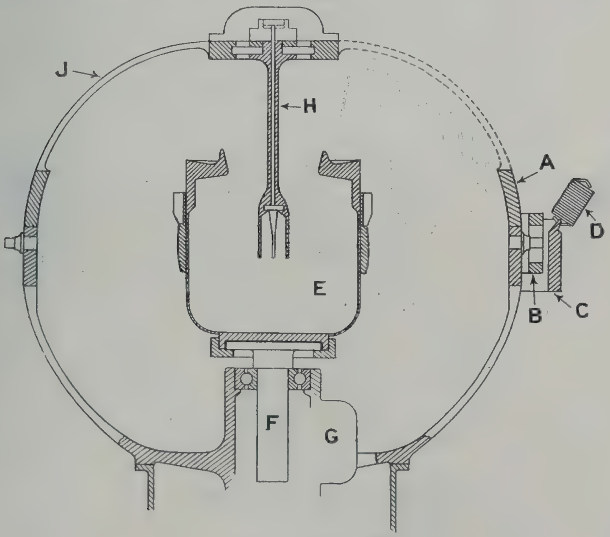


FIG. 249.

work, inside of which is a bowl and card. The framework *A* (Fig. 249), is pivoted in a gimbal ring *B*; this ring is pivoted in another *C*, which is suspended by a large number of spiral springs *D* from the upper edge of the binnacle.

Inside the framework is the bowl *E*, the axis *F* of which can turn in ball bearings in the lower part of the framework. The rotation of the bowl relative to the framework is required in connection with the transmission system to the compass receivers, and is effected by means of an electrical apparatus *G* at the bottom of the framework. A stem *H*, supported by three arms *J*, is for the purpose of conveying the electrical current to the gyrostats, and for keeping the card central.

A section of a portion of the card is shown in Fig. 250. Attached to the float *K*, which is immersed in mercury contained in the bowl, is a conical tube *L*; at the bottom of this tube is the bearing surface *M* for the projection of the stem *H*, as shown in Fig. 251. At the top of the tube *L* is secured a triangular shaped casting *N*, which carries three gyro-casings *X*, *Y*, *Z*, in ball bearings.

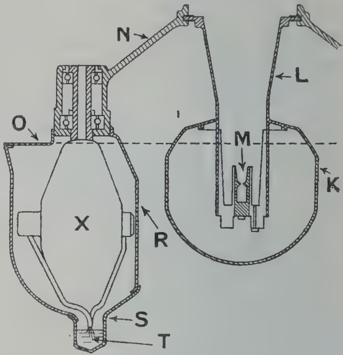


Fig. 250.

The graduations of the card are marked on the horizontal ring *O*, the graduations being the same as those of a magnetic compass, except that the degrees are marked from 0° to 359°. The South point of the card (180°) is on that radius of the card

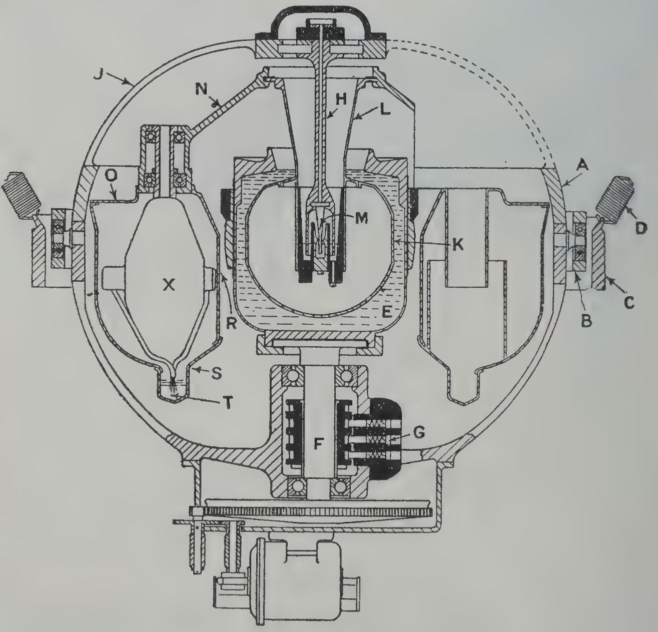


Fig. 251.

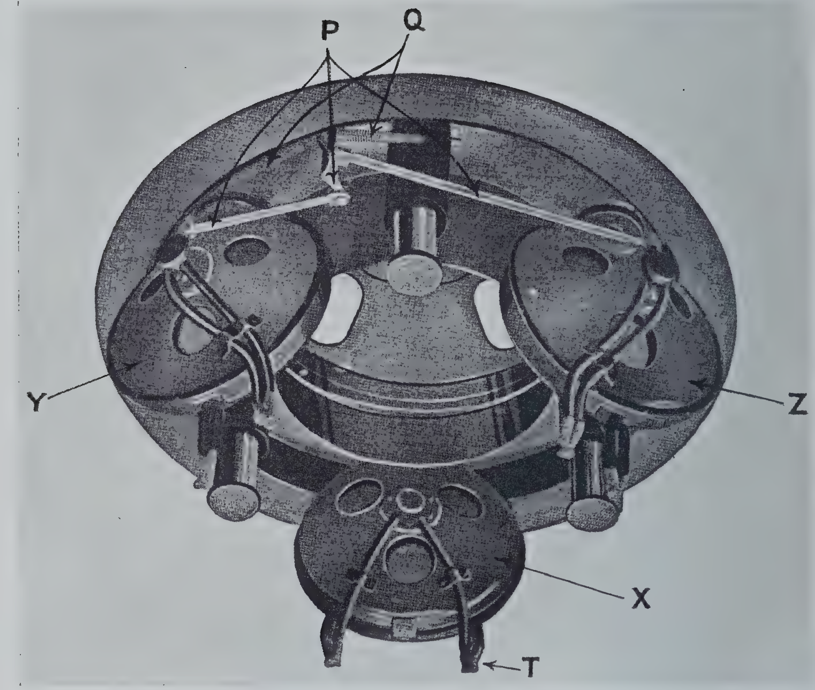


Fig. 252.

which intersects the stem of the gyro-casing *X*, the stems of *Y* and *Z* being 120° from that of *X*.

The axle of the gyro *X* is maintained parallel to the North and South line of the card by means of two spiral springs, and the axles of *Y* and *Z* make angles of 30° with the North South line of the card when in their central positions.

In Fig. 252 are shown the three gyro-casings, *X*, *Y* and *Z*, as viewed from below the compass card.

The casings *Y* and *Z* are connected by means of a system of three levers *P*, which only allows the casings to turn about their vertical stems in opposite directions. The position of the axles of the gyrostats are normally maintained at an angle of 30° on either side of the North and South line of the compass card, by means of two spiral springs *Q*.

The gyrostats are driven at 20,000 revolutions per minute, by means of three-phase induction motors, the directive force of the system being due to the action of *X* and the resultant effects of *Y* and *Z*.

325. Damping of the oscillations of, and applying the corrections to the "Anschütz" (three gyro) gyro-compass.—In order to introduce the vertical couple necessary to provide the damping described in § 318, the three gyro-casings *X*, *Y*, *Z*, are enclosed in a casing *R*, carried by the floating system (Fig. 250), at the bottom of which is a circular trough *S*; this trough is partially filled with oil, and is divided into small compartments by means of diaphrams which have orifices in them. When the compass is not pointing true North, the card is tilted, and the oil flows slowly to the lower side of the trough. On the North point of the card passing the meridian, the card commences to tilt the other way, the oil in the trough comes into play, and acts against the tendency to tilt, and so retards the rate of precession. The oil slowly crosses the trough, and the flow is so restricted by means of the diaphrams, that the oil always just reaches that side of the trough which is about to rise owing to the continual alteration in the tilt of the card. The result is that the North point of the card traces a spiral (§ 318) and comes to rest in the direction of true North in about $2\frac{1}{2}$ to 3 hours.

The oil in the trough is also made use of to provide lubricant to the bearings of the three rotors by means of the wicks *T*.

Let us now consider the effect of a ship's motion in a sea way on the indications of the gyro-compass, and let us first consider the effect of the North or South point of the compass card being depressed. It will be seen from Fig. 252 that all three gyrostats will precess in the same direction, and since the two gyrostats *Y* and *Z* are connected together by a system of levers as shown, the angle between their axles and the North South line of the compass card will not change, but the card will revolve to the right or left due to the precession of all three gyrostats. The card will subsequently regain its horizontal position after one or two oscillations, the period of which is about 90 minutes.

If the East or West point of the card is depressed, *X* is merely turned in its plane of rotation, and therefore does not precess; *Y* and *Z* have opposite ends of their axles depressed, and consequently precess equally in opposite directions, causing a disturbance of the equilibrium of the two springs *Q*, which tend to maintain these gyrostats in their normal positions relative to the compass card. The springs reassert themselves and the card regains its horizontal position after a few swings, the period of which is about one minute. This equal and opposite precession of the gyrostats *Y* and *Z* does not deflect the compass card, but its effect is to greatly increase the period of oscillation of the compass in the East West vertical plane, and thus avoid any possibility of synchronism between the periods of the ship and compass (§ 320).

Two levels are fitted on the card: that which lies North and South indicates when the compass has finally settled down in the direction of the meridian, by its bubble then remaining stationary; that which lies East and West merely indicates the horizontality, or otherwise, of the card in that direction.

The angle δ, which depends on the latitude, course and speed, should be applied in the same manner as the deviation of a magnetic compass, as follows:—

Given the compass direction, to find the true—

Apply δ + or − according as the course is South or North.

Given the true direction, to find the compass—

Apply δ + or − according as the course is North or South.

The values of δ for various latitudes, courses, and speeds are calculated from the formula in § 319, and tabulated on cards which are supplied with each compass.

To test the accuracy of the gyro-compass, its deflection from the meridian should be found in the same way as the deviation of the magnetic compass (§ 306); this deflection, if the instrument is correct, should agree with the tabulated value of δ.

The Anschütz master compass, which has been briefly described above, is usually mounted in a well protected position, generally in the lower conning tower, and receivers or repeating compasses are provided similarly to the Sperry gyro-compass.

326. The "Anschütz" receivers.—An "Anschütz" receiver is illustrated in Fig. 253; its card is graduated in a similar manner to that of the master compass, and concentric with it is a smaller card which makes one revolution for every alteration of course of ten degrees. The whole circumference of the latter is graduated from 0 to 10 and each space is called a degree; each space which represents a degree is subdivided into

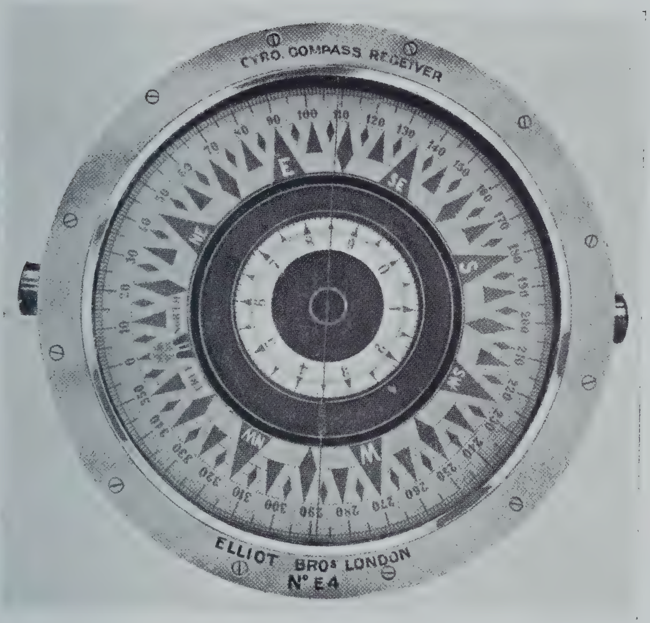


Fig. 253.

tenths. The card is driven through gearing by an electric motor, and may be mounted in any position, but it is generally mounted vertically on a bulkhead, or horizontally on a pedestal.

As far as the course is concerned the direction of the lubber's point is immaterial, but, if the receiver is to be used for taking bearings, the lubber-line should be fore-and-aft, in order that the North South line of the receiver card may be parallel to that of the master compass. For this reason, when mounted on a manœuvring platform, the receiver is supported in gimbals, and is fitted with an azimuth mirror, very similar to that described in § 301. The inner compass card enables the direction of the ship's head to be read off with great accuracy, and when the ship is under way the card is almost continuously moving as the ship yaws slightly to the right or left of her course; it is also of considerable value when conning the ship, altering course, &c., because the instant at which the ship has ceased to swing can be readily determined.

As the deflection due to the course and speed of the ship is not allowed for in the master compass, it must be applied to all courses steered, or bearings taken, with the receivers, in the manner explained in the previous article.

When laying off courses, or lines of bearing obtained from observations with this compass, it is convenient to lay them off from the outer graduated circle of the compass rose engraved on the chart, because this is graduated in the same manner as the card of the gyro-compass (§ 23).

CHAPTER XXVIII.

THE SEXTANT.

327. The principle of the sextant.—The sextant is an instrument designed for the measurement of angles, particularly at sea, where the motion of the ship precludes the use of fixed instruments. As will be understood from Part I., the sextant is a most important navigational instrument, since it is used in nearly all observations for determining the ship's position.

The optical principle embodied in the sextant is that if a ray of light suffers two successive reflections in the same plane by two plane mirrors, the angle between the first and last directions of the ray is twice the angle between the mirrors. This may be shown as follows.

Let a ray of light from the point X, Fig. 254, suffer reflection at the points I and H of two plane mirrors whose planes are perpendicular to the plane of the paper, the angles to the normals at I and H being θ and ϕ respectively. Let the ray XI intersect the last ray in A, so that IAH is the angle between the first and last rays. Let the normals to the mirrors intersect at B, so that IBH is the same as the angle between the mirrors.

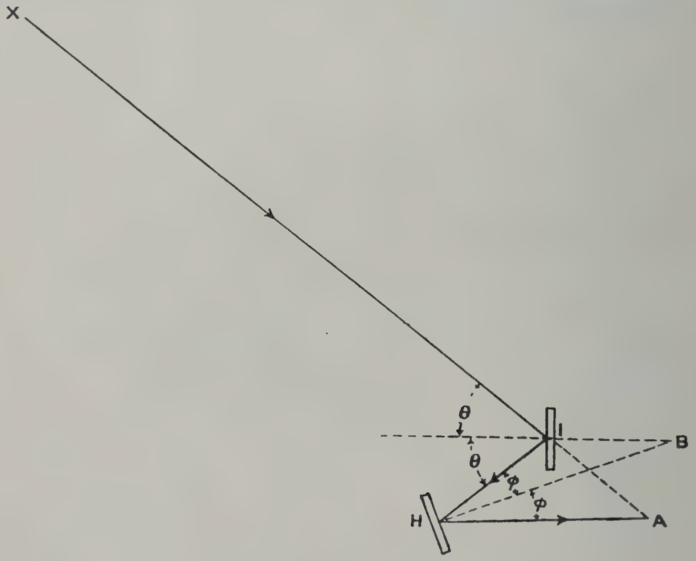


FIG. 254.

In the triangles *IAH* and *IBH* we have

$$IAH = 2\theta - 2\phi$$

and

$$IBH = \theta - \phi$$

Therefore $IAH = 2\,IBH$; that is to say, the angle between the first and last directions of the ray is twice the angle between the mirrors.

Now, suppose that a ray of light from another point *Y*, Fig. 255, coincides with the ray *HA*: then the angle subtended at *A* by the arc *XY* is the angle *XAY*, or twice the angle between the mirrors.

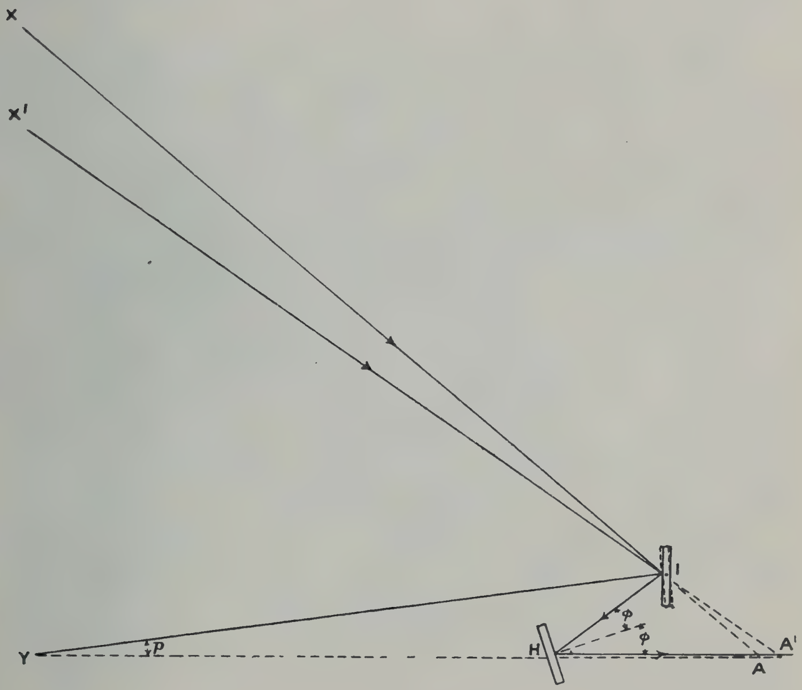


Fig. 255.

Again, suppose that the mirror *I* can revolve about a fixed axis, perpendicular to the paper, then, if *X′* is another point in the plane of *XY*, the ray from *X′*, after reflection at *H*, can be made to coincide with *YA* by suitably revolving the mirror *I*, and the angle *X′A′Y* is twice the new angle between the mirrors. Thus, with the aid of the two mirrors, we can find the angle subtended by the arcs *YX*, *YX′*, &c., at various points along *YH* produced.

Now

$$XIY = XAY + AYI$$

and

$$\sin AYI = \frac{IH \sin 2\phi}{IY}$$

so that, if we measure angles at the fixed point I by means of the two mirrors, and denote the angle AYI by p, we have

$$XIY = 2\ (\text{angle between mirrors}) + p,$$

where

$$\sin p = \frac{IH \sin 2\phi}{IY}.$$

From the following description of the sextant it will be seen how the optical principle is embodied, and it should be observed that the angle p, called the sextant parallax, may generally be neglected, since IH is very small compared with the distance between the points I and Y.

328. Description of the sextant. — The sextant, Fig. 256, consists of a metal frame A, one edge of which is a circular arc CD; an arm B, called the index bar, can rotate about the centre of the arc. Standing perpendicular to the frame is a small frame H, in which is fitted a glass mirror called the horizon glass, the upper part of which is usually unsilvered, small screws being provided for adjusting the position of the mirror. Standing on the index bar over the centre of the arc is another small frame I, which carries a mirror called the index glass.

The arc CD is graduated, and the graduations are so arranged that, when the index glass is parallel to the horizon glass, an index on the index bar points to the zero O of the scale. The graduations are continued over a small arc on the other side of O, which is called the arc of excess. The index bar may be secured in any position on the arc CD by means of a clamping screw beneath it, and, when clamped, it may be given a slow motion to one side or the other by means of a screw E, called the tangent screw. The setting of the index on the scale may be accurately determined by means of a vernier, which will be explained in § 329; a small microscope F, carried on an arm pivoted on the index bar, is provided to facilitate the reading of the graduations.

The telescope G is carried in a collar J, which can be raised or lowered at will by means of a milled head K beneath the frame; the telescope is so arranged that its axis makes the same angle with the plane of the horizon glass, as the line joining the centres of the index glass and horizon glass. Two sets of coloured shades, L and M, are provided for use when taking observations of bright objects. On the opposite side of the frame to that shown are three legs and a wooden handle N.

When measuring an angle subtended by two objects, the observer, looking through the telescope, sees one object through the unsilvered part of the horizon glass, and the image of the other object after reflection at the index and horizon glasses; the relative amount seen of each object is governed by the height of the collar. Therefore, from the previous

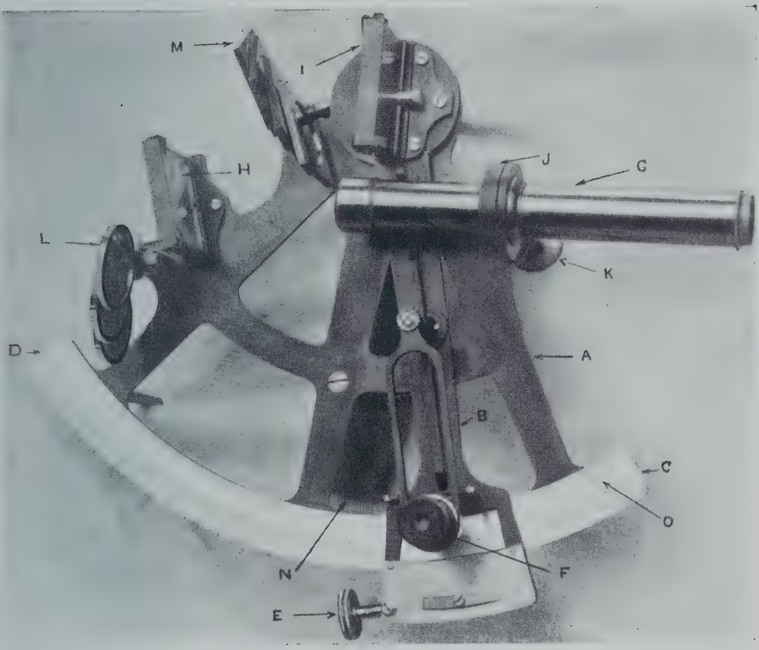


Fig. 256.

article, we see that the angle subtended by two objects at the index glass is twice the angle between the index and horizon glasses + the sextant parallax. Now the angle through which the index has moved, from the zero of the scale, is the same as the angle between the mirrors; therefore, in order that the reading of the index on the graduated arc may represent twice the angle between the mirrors, each degree of the arc is graduated into two equal parts called degrees. These are again subdivided into six equal parts, each of which is called ten minutes.

329. The vernier.—When it is required to read a small graduated arc, such as that of a sextant, to a close degree of accuracy, a supplementary graduated arc, called a vernier, is employed. The vernier fits closely to the graduated arc of the instrument under consideration, and the method of ascertaining the correct reading will be understood from the following.

Let the value represented by the distance between two adjacent graduations of the instrument be a, and suppose that it is required to read the setting of the index to a degree of accuracy d, and that $d = \frac{a}{n}$. Take an arc of the same curvature and of such a length as to represent $(n - 1)a$, and divide it into n equal parts; then the value represented by the length of each division of this arc is $\frac{(n-1)a}{n}$; so that the difference between the values represented by a length of a division of the scale and a length of a division of the arc is

$$a - \frac{(n-1)a}{n} = \frac{a}{n} = d.$$

In Fig. 257 let CD be the scale of an instrument graduated from right to left and VW a vernier. Let the index of the instrument and the zero of the vernier coincide at V, the graduations of the vernier being numbered as shown.

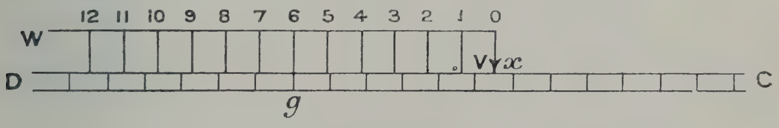


FIG. 257.

Let O be the zero of the arc, then the setting of the index is Ox+a small amount, xV. In order to read the exact setting of the index, look along the vernier and note that the sixth graduation exactly coincides with the graduation g of the scale, then

$$xV = xg - V6 = 6d.$$

Thus the setting of the index is $Ox + 6d$, and it will be noticed that the limit of error in reading is d.

In a sextant, as the arc is generally graduated to read every 10′, the vernier is usually constructed so that 120 of its divisions are equal to 119 divisions of the arc; as this would give *d* a value of 5″, which is a degree of accuracy unnecessary in navigation, only every other graduation of the vernier is engraved, so that the setting of the index of the sextant can be read to 10″.

When reading off angles on the arc of excess, it is necessary to read the vernier from the opposite end—that is, from left to right—and to count the divisions from the left.

The vernier of any instrument, should always be in perfect contact with the scale of the instrument, in order that there may be no doubt as to which graduation of the vernier is in coincidence with a graduation of the scale.

330. The sextant telescopes.—A sextant is generally provided with two telescopes and a plane tube, the latter, as its name implies, being merely a tube, with no lenses, provided for the purpose of ensuring that the line of sight is parallel to the plane of the instrument. It is of little practical value, because a telescope should always, when possible, be employed when taking observations.

The principal telescope is called the inverting telescope, because, on account of the arrangement of the lenses, objects seen through it appear to be inverted. It is provided with two eye-pieces, one of which is of higher magnifying power than the other; each of them is fitted with cross-wires at its focus in order to define the line of collimation, which is the line joining the focus to the centre of the object-glass. The eye-piece of higher power generally has two cross-wires, while the other has four.

Besides the inverting telescope, sextants are usually provided with a star telescope, which is bell-shaped and has a large object-glass; it is an erecting telecsope, and its magnifying power is not high, being intended for use when taking observations of stars. Its large object-glass is for the purpose of overcoming the restriction of the field of view due to the erecting eye-piece. The star telescope is also of considerable value when measuring angles between two terrestrial objects, for it ensures that the contacts are made exactly, and it should always be used when taking such observations.

A certain number of coloured eye-pieces are provided, which may be placed over the eye-piece of the telescope when it is desired to reduce the brilliancy of the direct and reflected objects equally, such as, for example, when taking observations of the sun in an artificial horizon; this obviates the danger of introducing an error due to a possible lack of parallelism in the glass shades (§ 148).

331. The sextant parallax.—It has been explained that the angle subtended at the index glass is equal to the angle shown on the sextant + the sextant parallax. Now from § 327 we have

$$\sin p = \frac{IH \sin 2\phi}{D},$$

where D is the distance of the object seen through the unsilvered portion of the horizon glass. From this formula we see that the greater the distance of the object Y the smaller is the parallax; for example, in a sextant in which 2ϕ is 33° 06′ and IH 3 inches, we have the following corresponding values of p and D:—

p	D
1″	5·33 miles.
10″	4·6 cables.
60″	156 yards.

Therefore, when an angle is being observed between two objects, one of which is very close to the observer, the sextant telescope should be directed to that object which is furthest away. The error due to sextant parallax may be allowed for as explained in §336, but it will be seen that, unless the distances of the objects are very small indeed, the sextant parallax is inappreciable and may be neglected.

332. The errors of the sextant.—We have now to consider the various errors to which the sextant is liable, and the means by which they may be ascertained and eliminated. The principal errors may be summarised as follows:—

(1) Error of perpendicularity. The index glass should be perpendicular to the plane of the instrument.

(2) Side error. The horizon glass should be perpendicular to the plane of the instrument.

(3) Collimation error. The line of collimation should be parallel to the plane of the instrument.

(4) Index error (I.E.). The horizon glass should be parallel to the index glass when the index is at zero.

(5) Centering error (C.E.). The pivot on which the index glass revolves should be concentric with the graduated arc.

Besides these there are numerous small errors due to faulty construction and graduation, and to lack of parallelism between the back and front of each of the glass mirrors and shades.

A sextant, before being purchased, should be sent to the National Physical Laboratory at Teddington, where a complete examination will be made, and any errors will be pointed out to the makers for rectification. Provided the errors are small, a certificate is granted as explained in §337. Since it is probable that ill-treatment, or change of temperature, may subsequently introduce error in the shades, it is advisable, as explained in §148, when taking observations of the sun in an artificial horizon, to use one of the coloured glass eye-pieces; any error in these will not affect the observations, because both the direct and reflected images are seen through it. We shall now deal with the five principal errors separately.

333. The error of perpendicularity.—*The index glass should be perpendicular to the plane of the instrument.* To examine if this is so, set the index near the middle of the arc. Hold the instrument horizontally with the index glass towards you, and look obliquely into the index glass, the eye being in the plane of the instrument and near the index glass. The reflected image of the arc should now be seen in an unbroken line with the arc itself. Should the line appear broken, the index glass needs adjustment before observations are taken, and this can be effected by means of a small screw in the centre of the upper part of the frame of the index glass.

334. Side error.—*The horizon glass should be perpendicular to the plane of the instrument.* To examine if this is so, the error of perpendicularity should be first eliminated; then, with the inverting telescope in place, look at some well-defined distant object, preferably a heavenly body, and move the index towards and beyond the zero of the scale. Should the reflected image pass exactly over the direct image no error exists, but should it not do so the horizon glass needs adjustment before observations are taken, and this can be effected by means of a small screw in the centre of the upper part of the frame of the horizon glass.

335. Collimation error.—*The line of collimation should be parallel to the plane of the instrument.* To examine if this is so, the error of perpendicularity and side error having been eliminated, with the inverting telescope in place, turn the eye-piece until two of the wires are parallel to the plane of the instrument. Select two heavenly bodies, the angular distance between which is not less than 90°, and bring them into accurate contact on one wire of the telescope; before the angular distance changes, move the sextant until the bodies are on the other wire, when they should still be seen in contact; if not in contact there is collimation error, and this should be corrected by means of the two screws on the collar. It may be noted that if the two bodies appear to separate on the wire furthest from the plane of the instrument, the object-glass end of the telescope droops towards the plane of the instrument, and *vice versâ*, but it should be remembered, when interpreting this rule, that the telescope inverts the positions of the cross-wires. If the adjustment is accurately made, any two images which are seen in contact on one wire will appear to slightly overlap if moved to the centre of the telescope.

The line of collimation may be approximately tested as follows. Place the sextant horizontally on a table, and lay the inverting telescope on the arc, so that the tube of the telescope rests on the arc. The axis of the telescope should now be parallel to the plane of the instrument. Look through the telescope and make a mark on some object, the distance of which is not less than 20 feet, to coincide with the centre of the cross wires. Screw the telescope into the collar and make another mark above the first, at a distance from it equal to the vertical distance between the two positions of the telescope. The upper mark should now be seen in the centre of the cross wires; should it not be so the collar requires adjustment.

When adjusting the collar, one screw should first be eased back, and then the other tightened a similar amount.

336. Index error.—*The horizon glass should be parallel to the index glass when the index is at zero.*—In Fig. 258 let DV be the setting of the index bar when the horizon glass is parallel to the index glass, then V is the point at which the graduation should be zero. If the graduation is zero at some other point O, the measurement of any angle will be in error by OV, which will be $-$ or $+$ to the measured angle according as V is on the arc or on the arc of excess (off the arc).

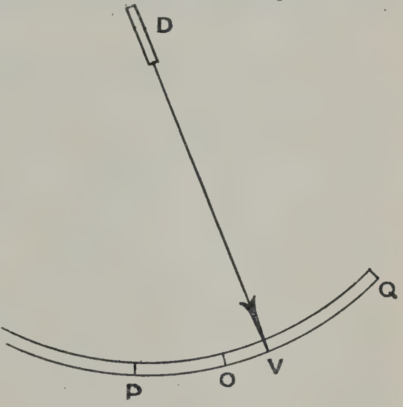


FIG. 258.

Now when the index glass is parallel to the horizon glass and both are perpendicular to the plane of the instrument, the direct and reflected images of a very distant object, such as a heavenly body, appear to coincide. Therefore the index error may be found by bringing the direct and reflected images of a star into coincidence, the collimation error having first been eliminated; the reading of the index will be the index error, $+$ or $-$ as indicated above.

If no heavenly body is available, the index error may be found by aid of a distant terrestrial object or the sea horizon.

The index error may also be found by measuring the sun's diameter on and off the arc. Let P and Q be the positions of the index when the sun's diameter is measured on and off the arc respectively, then the readings on and off the arc are OP and OQ, and, since $VP = VQ$, we have

$$OP + OV = OQ - OV$$

$$\therefore\ OV = \frac{OQ - OP}{2}$$

so that the index error OV is half the difference of the readings, being + when the reading off the arc (OQ) is greater than the reading on the arc (OP), and *vice versâ*. Since refraction affects the upper and lower limbs of the sun to a different extent, the observation should be made between the right and left limbs. In order to check the accuracy of the observation, it should be remembered that the sum of the two readings divided by four should give the semi-diameter of the sun, and should therefore agree with the semi-diameter tabulated in the Nautical Almanac for the day in question.

When taking observations of the sun in an artificial horizon, the index error may be found in a similar manner, by making use of the reflected image of the sun as seen in the artificial horizon.

The index error, being a correction which is the same for every angle observed, need not be eliminated, but, being very liable to change, should be determined whenever observations are taken.

Should it be desired, the index error may be eliminated as follows:—With the index set to zero, direct the inverting telescope at a star, and bring the two images into coincidence by means of a small screw at the base of the frame of the horizon glass. As this adjustment throws out the original adjustment of the side error, the latter should now be readjusted; another adjustment of the index error should now be made, and so on till the instrument is correct.

The adjusting screws should only be touched when necessary, and then only with caution; it is better that the errors should exist, provided that they can be allowed for nearly, than that the instrument should be damaged by attempts at a perfect adjustment by inexperienced persons.

When it is necessary to measure the angle subtended by two objects which are close to the observer, the sextant parallax may be determined and allowed for, in conjunction with the index error, by bringing the direct and reflected image of the object Y, Fig. 248, into coincidence; the angle shown on the sextant is then index error + parallax, and this may be applied as a correction to any angle subsequently measured between Y and another object, provided that the sextant telescope is directed to Y.

337. Centering error.—*The pivot on which the index glass revolves should be concentric with the graduated arc.* The error introduced by the eccentricity of the pivot is different for different angles measured, but included in what is generally known as centering error are the various residual small errors mentioned in § 332.

When a sextant is under examination at the Royal Physical Laboratory, the centering (total) errors for various angles are observed and tabulated. The result of the examination is stated on a certificate, which is pasted on the inside of the lid of the sextant box. An A certificate is granted when the centering error does not exceed 40″, the errors being found for every fifteen degrees of the arc; a B certificate is granted when the centering error does not exceed 2′, the errors being found for every thirty degrees of the arc; no certificate is granted if the error exceeds 3′.

The centering error corresponding to an observed angle should be applied in the same manner as index error, but it should not be assumed that the centering error remains constant at the tabulated value for a very long time, and therefore the centering error for various angles should occasionally be redetermined, and this may be done as follows.

In Fig. 259 let Z be the zenith of an observer O, and CQ the plane of the equator. Let X_1 and X_2 be the true places of two heavenly bodies South and North of the zenith, and approximately of the same altitude. Let the centering error, corresponding to the altitudes observed in an artificial horizon, be $+c$, then the double altitudes observed are too small by c, the altitudes too small by $\frac{c}{2}$ and the zenith distances too great by $\frac{c}{2}$. Therefore, due to the altitude of X_1, the observer imagines his zenith to be at Z_1, and, due to the altitude of X_2, the observer imagines his zenith to be at Z_2.

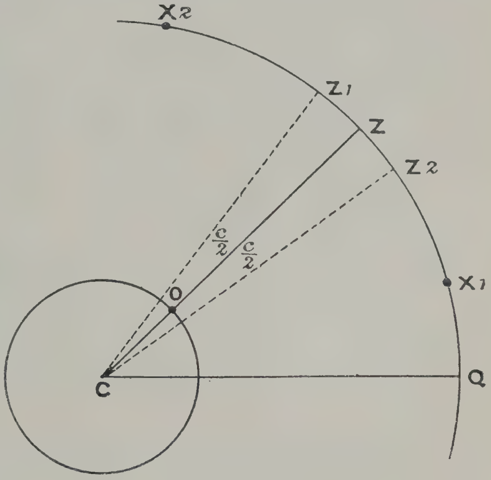


Fig. 259.

Now it is obvious from the figure that

$$Z_1CQ - Z_2CQ = c,$$

so that the centering error, corresponding to the observed angle in the artificial horizon, is equal to the difference between the latitudes obtained from the two observations; it is + when the latitude found from the body which is on the equatorial side of the zenith is the greater, and *vice versâ*.

This observation for centering error should be taken in an artificial horizon, on account of the possibility of the dip of the sea horizon being differently affected by refraction in the North and South directions, and care should be taken to apply the full corrections for refraction to the observed altitudes.

The centering error may also be found by correcting the observed angular distance between two stars for index error and refraction, and comparing the result with the actual angular distance as found by calculation. In order that it may be possible to easily correct the observed distance for refraction, the stars should be on the same circle of altitude, that is, their azimuths should be the same, or opposite, and their altitudes should be observed. The correction for refraction is the difference or sum of the refractions corresponding to the two altitudes, according as the azimuths of the stars are the same or opposite.

The true angular distance X_1X_2 in Fig. 260 may be easily found, for in the triangle PX_1X_2, PX_1 and PX_2 are the polar distances of the stars, and the angle X_1PX_2 is the difference between their right ascensions.

To take the observation, two bodies should be selected by eye which appear to have the same azimuth. When observing the angular distance, the observer should note whether the plane of the sextant is vertical, in order to see if the bodies have the same azimuth. At the same time as the altitudes are observed, if the compass bearing is taken, the names of the bodies may be found from "What Star is it?" The error in the centering error due to the bodies not having exactly the same azimuth is of no importance.

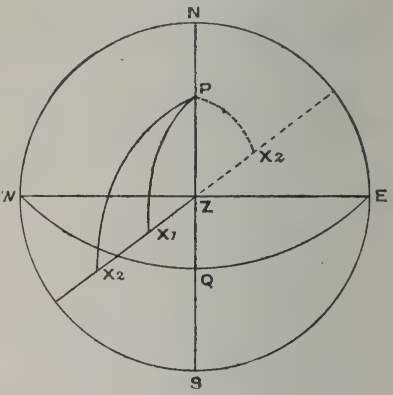


Fig. 260.

The angular distances between a large number of pairs of stars, together with the data for finding at what time the two stars of any pair have the same azimuth, are tabulated in a book entitled "Stars and Sextants."

338. Care and use of the sextant.—The sextant should always be handled with great care, because a slight blow is liable to derange the adjustments. The instrument should be lifted and held by means of the frame or handle and not by the arc. When screwing a telescope into the collar, care should be taken not to burr the threads. The instrument should never be left exposed to the sun's rays because heat tends to warp the frame; and, after use in damp weather, all parts of it should be carefully dried in order to preserve the silvering of the glasses.

The sextant should not be kept in a drawer, on account of the shocks which it may receive when the drawer is opened or closed, which are often sufficient to derange the various adjustments. A proper stowage position, preferably on a shelf, should be provided and fitted with battens to hold the sextant box securely when the ship is in a seaway.

When measuring angles with a sextant, it is important that the objects should be observed in the centre of the field of the telescope, in order that the ray from each of the objects may coincide with the line of collimation.

It is advisable to mark the various eye-pieces so that they may be readily set to suit the vision of the observer ; such a mark saves the necessity of focussing the telescope on each occasion of using it.

When measuring the altitude of a heavenly body above the sea horizon, care should be taken that the angle is observed in the vertical plane. The vertical angle is the smallest which is subtended by the body and any point of the horizon ; consequently, if the sextant is slightly turned from side to side while taking the observation, the heavenly body will appear to move on the arc of a circle which is convex to the horizon. By means of the tangent screw, this arc of a circle may be raised or lowered with reference to the horizon, until the body, while apparently passing to and fro, is seen to just graze the horizon ; the altitude of the body at that instant is shown on the sextant.

CHAPTER XXIX.

THE CHRONOMETER.

339. The principle and general description of the chronometer.—In this chapter we have to give an account of the instrument which is designed to tell us the G.M.T. at any instant, and, since mean time is measured by the angle traced out by the mean sun as it moves at a uniform rate, it is most essential that the movement of the instrument should be uniform.

Let the axle *A*, Fig. 261, of a wheel, be mounted in bearings in which friction is a minimum, and let a spiral spring, whose plane is parallel to that of the wheel, have one of its ends attached to the axle and the other to a fixed point *B*.

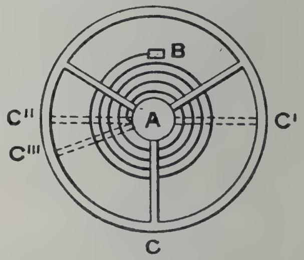


Fig. 261.

If the radius *AC* is turned by the hand into the position *AC′*, a certain amount of work is stored in the spring, and, if the radius is released, this work is converted into kinetic energy as the wheel turns in the reverse direction; at the position *AC* the energy is a maximum. The wheel turns beyond *AC* and, in the absence of all friction, comes to rest at the position *AC″*, symmetrical with *AC′*, the energy which the wheel had at *C* being now stored in the spring. The spring now starts the wheel in the original direction and it turns back to the position *AC′*, and so on. In the absence of friction and resistance of the air, and assuming that the spring does not lose its elasticity, and that the shapes of the wheel and spring are not altered by changes of temperature, this movement would continue indefinitely, each oscillation being performed in the same time. Such a mechanism, called a balance, would, therefore, afford a means of measuring an interval of time by the number of oscillations made in that interval, and the principle involved, but modified so as to take account of friction, is the principle of the chronometer.

On account of friction, the wheel, after release at *AC′*, comes to rest at some position *AC‴* very near to, but short of, *AC″*, such that the circular measure of the angle *C″AC‴* multiplied by the frictional torque on the wheel, is the energy lost. In order to make up for this continual loss, energy is communicated to the balance by means of a mechanism called

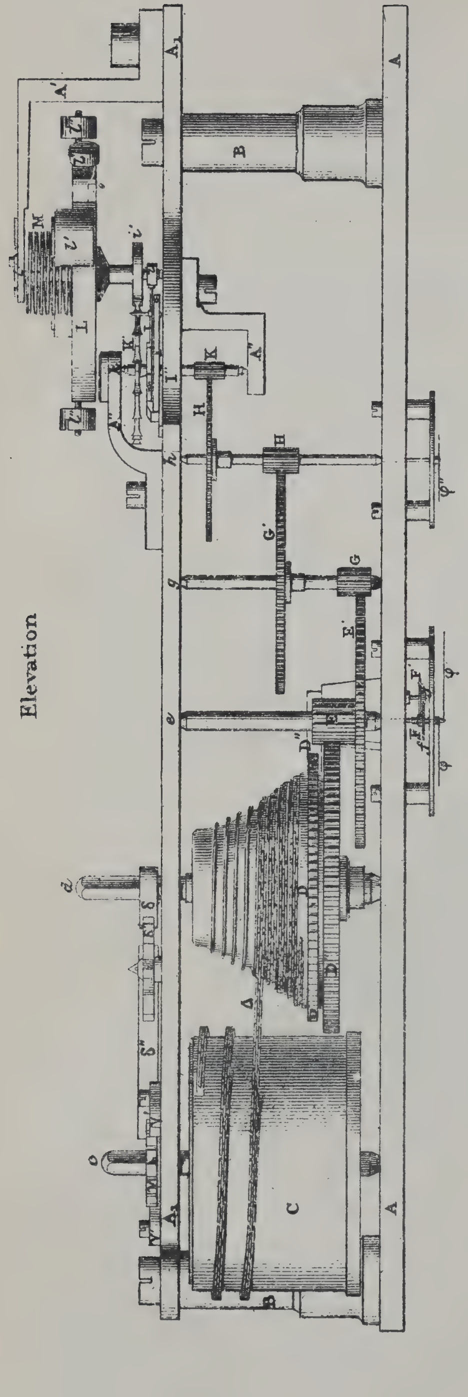


Fig. 262

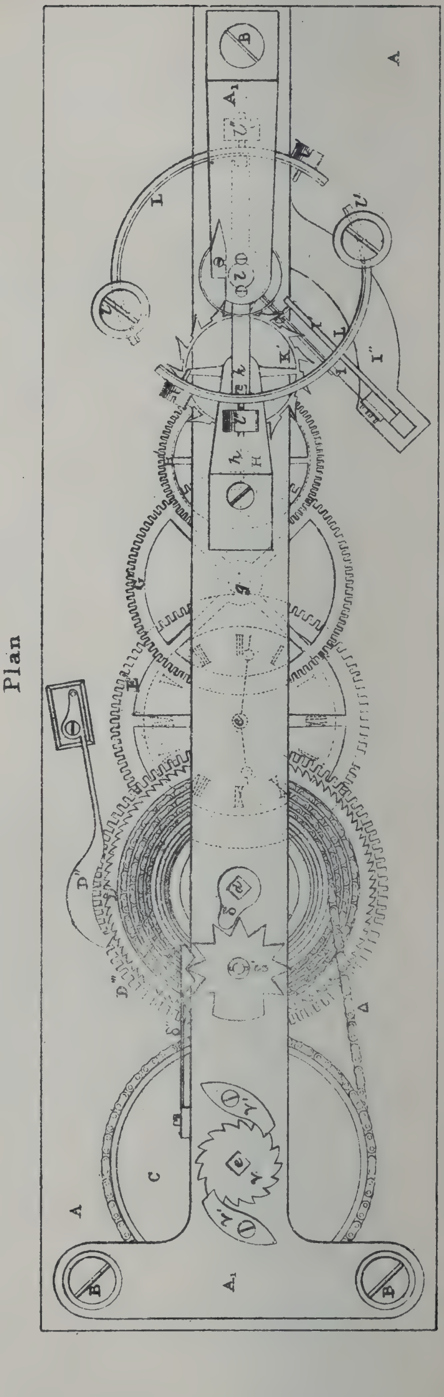


Fig. 263

the escapement. This energy is derived from the mainspring and transmitted through a train of wheels. In addition to transmitting energy from the driving mechanism to the balance, the train has another function—namely, to count the number of oscillations of the balance, and it performs this function by the agency of a special mechanism called the motion work. Thus the mechanism of a chronometer may be divided into the following:—

The balance.
The escapement.
The train.
The motion work.
The driving mechanism.

Figs. 262 and 263 represent in elevation and plan the mechanism of a chronometer, the axles of the various wheels being, for simplicity, shown in the same plane. A and A' are two plates, called the pillar plate and top plate respectively, which are held parallel to one another by means of the pillars B, B. Between these two plates is contained the driving mechanism and the train; on the outside of the pillar plate is the motion work, by means of which the hands are made to revolve concentrically at their correct relative speeds; on the outside of the top plate is the balance and escapement.

In English chronometers the escapement is usually between the top and pillar plates.

The mechanism is contained in a brass covering which is supported by gimbals in a wooden case. The case is provided with two lids, the outer of wood and the inner of glass, in order that the face of the chronometer may be seen without exposing the instrument to misadventure. The gimbals may be locked when necessary, as, for example, when the instrument is being moved. At the bottom of the brass case is a hole for the insertion of the key, and this is kept closed by means of a revolving shutter which is held in place by a spring.

340. The driving mechanism.—The driving mechanism comprises a drum C, called the barrel, and a truncated cone D, called the fusee, the two being connected by a chain Δ, called the fusee chain. The barrel C contains a coiled spring, called the main spring, the inner end of which is attached to the barrel axle c, which is prevented from turning by the two pawls γ', γ' acting against the barrel rachet γ fixed on the axle; the outer extremity of the mainspring is attached to the inside of the barrel. When the spring has been put in a state of tension by winding, it exerts a tangential pull on the barrel C, since the axle c is fixed, and consequently a tension is set up in the fusee chain Δ. This tension gradually diminishes as the spring unwinds, but since the chain leads on to the fusee at points which are further and further from the axle, the diminishing tension acts on the fusee at an increasing arm, and so exerts a constant torque.

In order that the mainspring may exert the required tension, and also that, when nearly run down, its various turns may not bind on one another, an initial tension is given to the mainspring by means of the squared head at the end of the barrel axle *c*, the axle being subsequently secured by the pawls γ', γ'.

341. The winding and maintaining mechanism.—In order to wind the mainspring, the key is placed on the squared head of the fusee axle *d*, which, on being turned, rotates the fusee, and thus, by means of the chain, the barrel. In order to avoid the possibility of overwinding, a small finger-piece δ is secured to the fusee axle, and so arranged that, at every revolution of the fusee, it moves one tooth of a star wheel δ'. When the instrument is fully wound, the finger piece takes against the plane part of the star wheel δ' and checks further winding. At the other end of the fusee axle is a pinion, which, on the fusee being turned, drives a wheel which indicates, by means of a hand on a small dial on the face of the chronometer, the number of hours which have elapsed since the last winding. This contrivance is called the up and down indicator, but is not shown in the Figures.

The toothed wheel D''', called the great wheel, drives the train, and in order that the action of winding may not affect the great wheel, and that the power transmitted by this wheel to the train may remain constant during winding, the great wheel is connected to the fusee by a special mechanism at the base of the fusee, called the maintaining mechanism, Fig. 264. The ratchet wheel *a* is screwed to the base of the fusee; the ratchet wheel D', which is concentric with the fusee, Figs. 262 and 263, carries two pawls, *b*, *b*, which engage with the ratchet wheel *a*. The ratchet wheel D' is connected by means of a spring *xy* to the great wheel D''', *x* being the point of attachment to the ratchet wheel and *y* to the great wheel. A pawl D'' engages with the ratchet wheel D'.

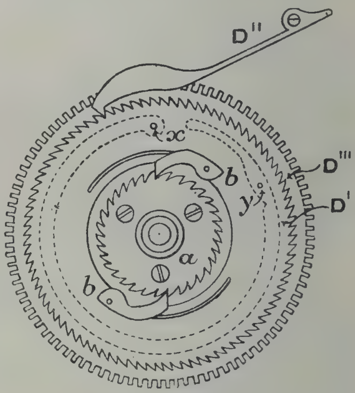


FIG. 264.

Let us now consider the action of this mechanism under ordinary circumstances and during the winding of the chronometer.

While the chronometer is going, the fusee revolves in a clockwise direction, carrying with it the ratchet wheel *a*, which turns the ratchet wheel D' in the same direction by means of the pawls *b*, *b*. The turning of D' causes the spring

xy to drive the great wheel D''' and, in so doing, puts the spring xy in a state of tension.

When the chronometer is being wound, the ratchet wheel a is turned in an anti-clockwise direction, and its teeth slip under the pawls b, b. The ratchet wheel D' is prevented from following this movement by the pawl D''. The tension of the spring xy now asserts itself, and causes the great wheel D''' to continue its movement.

342. The train.—Under this heading is included, with the exception of the escapement, the remainder of the mechanism which lies between the pillar and top plates. The great wheel D''', Fig. 261, engages with the pinion E, on the axle of which is fixed the wheel E'; this wheel and axle revolve once an hour. The wheel E' engages with a pinion G, on the axle of which is fixed a wheel G'; the wheel G' engages with a pinion H, on the axle of which is fixed a wheel H', called the seconds or fourth wheel, which revolves once a minute, and on the axle of which is mounted the seconds hand ϕ''. The wheel H' engages with the pinion K, called the escape pinion, on the axle of which is fixed the escape wheel K'.

343. The motion work.—The motion work is the name given to the mechanism which causes the hour and minute hands to revolve concentrically at their correct relative speeds. The axle eF, Fig. 262, of the pinion E, projects through the pillar plate, and on it is fixed, friction tight, a pinion F having a long boss or pipe, called the cannon pinion. On this pipe, which projects through the face of the chronometer, is mounted the minute hand ϕ', and the friction between the pipe and the axle is just sufficient to drive the motion work and hands. The cannon pinion F engages with a wheel F' which carries on its axle a pinion f; this pinion engages with the hour wheel f', mounted on a pipe external to and working freely on the minute hand pipe. This external pipe projects through the face of the chronometer and carries the hour hand ϕ. Thus any motion of the minute hand is conveyed by this train to the hour hand, the number of teeth in the various wheels and pinions being such, that the product of the numbers of teeth in the wheels is twelve times the product of the numbers of teeth in the pinions.

344. The escapement.—The escapement, Figs. 263 and 265, consists of the escape wheel K', the detent I, and the rollers i and i', called the discharging and impulse rollers respectively, mounted on the axle of the balance L. The detent I consists of four parts—a spring j attached to the top plate, a blade n terminating in a horn g and carrying a ruby stop o, called the locking pallet, and a gold spring p attached to the end of the blade and resting on the tip of the horn, with its end projecting slightly beyond. The discharging roller and the extremity of the detent are shown below the impulse roller in Fig. 265. On the discharging roller i is a small projection r called the discharging pallet, and on the impulse roller i' is a projection s called the impulse pallet; these pallets are of ruby or sapphire.

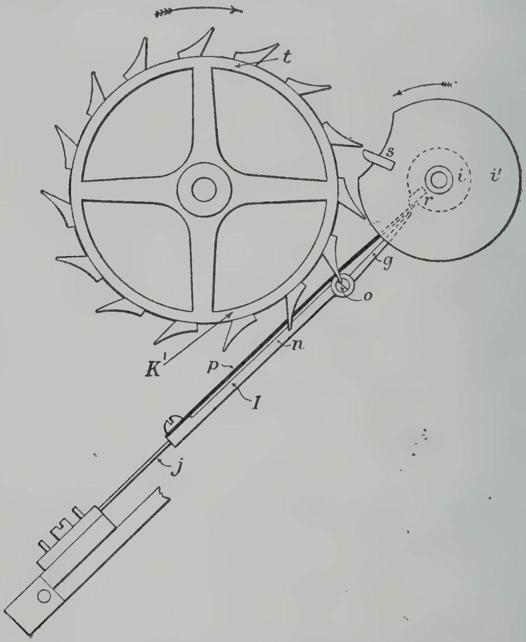


Fig. 265.

Let us suppose that the escape wheel K' is at rest with one of its teeth in contact with the locking pallet o, and that this tooth is just about to be released by the impact of the discharging pallet r on the tip of the gold spring p, due to the oscillation of the balance in the direction of the arrow; at the instant of impact the balance spring is in its position of equilibrium and the balance has its maximum velocity. When the tooth has been released, the spring j causes the locking pallet to catch the next tooth. Immediately after the release of a tooth the main spring sets the escape wheel in motion, and a tooth impinges on the impulse pallet s, thus supplying energy to the balance to make up for what has been lost in friction. The balance swings to its extreme position in the direction of the arrow, till the compression of the balance spring starts it in the reverse direction; on its return, the discharging pallet r passes the tip of the gold spring without affecting the locking of the next tooth, and the balance swings to its extreme limit and returns to repeat the cycle of operations. Thus for each complete oscillation of the balance, the escape wheel moves through an angle which is subtended by the arc between two teeth. As a general rule, the complete oscillation of a chronometer balance is performed in half a second; thus a chronometer beats half seconds, and each movement of the second hand corresponds to half a second of time.

345. The balance.—The balance consists of the balance wheel *L* and the balance spring *M*, Figs. 262 and 263. The axle of the balance wheel fits perpendicularly into an arm *k*. Attached to each extremity of the arm is a circular arc or rim *L*, which is formed of two strips of metal, the interior being of steel and the exterior of brass, and the latter being about twice the thickness of the former and melted on to it. A mass l', called a compensating mass, is carried on each rim, and can be secured in any position by means of a screw. At each end of the arm is a screw l'' called a regulating screw. A supplementary screw l''' is fitted on each rim as shown in Fig. 263.

On the lower part of the axle are the discharging roller *i* and the impulse roller i'.

The balance spring is a long and delicate helical steel spring, one end of which is attached to a stud on the bridge A', Fig. 262, and the other to a piece of metal, called a collet, on the axle of the balance. To ensure isochronism, as far as possible, the ends of the spring are formed in symmetrical curves, as shown in Fig. 266, in order that the whole spring may open and close symmetrically with regard to its axis, and that no stresses may be set up at the points of attachment.

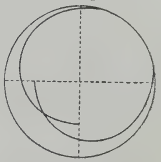


FIG. 266.

346. Time of oscillation of the balance.—Let *I* be the moment of inertia of the balance about its axis of rotation, and *M* the restoring torque due to the elasticity of the spring when the balance wheel has turned through an angle θ from its position of equilibrium, then, if *T* is the time of oscillation, we have

$$T = 2\pi \sqrt{\frac{I}{\frac{M}{\theta}}}$$

Now, if r_1 is the natural radius of the balance spring and r_2 the radius when the torque is *M*, we have from the theory of bending

$$\frac{M}{i} = \frac{E}{r_1} - \frac{E}{r_2},$$

where *i* is the moment of inertia of a section of the balance spring about its neutral axis, and *E* is the modulus of elasticity.

But if L is the length of the balance spring, we have

$$\theta = \frac{L}{r_1} - \frac{L}{r_2}.$$

Therefore $$\frac{M}{i} = \frac{E\theta}{L},$$

$$\therefore\ T = 2\pi\sqrt{\frac{IL}{Ei}}.$$

As a numerical example, the time of oscillation of the balance of a chronometer, may be found from the following details :—

Mass of balance - - - -	147 grains.
Radius of gyration of balance - -	·65765 inch.
Diameter of balance spring - -	$\frac{3}{8}$ inch.
Thickness - - - - -	$\frac{1}{90}$ inch.
Width - - - - -	$\frac{1}{60}$ inch.
Number of coils - - - -	$10\frac{3}{4}$.
Modulus of elasticity - - -	$3 \times 10^7 \frac{\text{lbs.}}{\text{in.}^2}$.

By substituting these values in the expression given above, the time of oscillation of the balance will be found to be approximately half a second.

As a chronometer balance, whose time of oscillation is uniformly and exactly half a second, oscillates

$$24 \times 60 \times 60 \times 2 = 172{,}800$$

times in 24 hours, it will be seen that an extremely minute error in the time of oscillation causes the chronometer to have a considerable daily rate.

347. The thermal compensation of the chronometer.—Let the time of oscillation when the temperature is x be $2\pi\sqrt{\frac{I}{S}}$ so that I is the moment of inertia of the balance wheel and S the elastic moment of the spring per unit angle of displacement of the balance $\left(\frac{Ei}{L}\right)$.

Let m be the mass of the balance wheel and k its radius of gyration at temperature x_0. Let α be the coefficient of expansion of the metal of the balance wheel, which we shall first suppose to be homogeneous. Then

at temperature x_0, $I = mk^2$,
at temperature x, $I = mk^2 [1 + \alpha (x - x_0)^2)]$.

Therefore when the temperature rises, I is increased by a constant quantity $(mk^2\alpha)$ multiplied by the square of the increase of temperature. Consequently if we plot I to a temperature base the resulting graph will be as shown in Fig. 267.

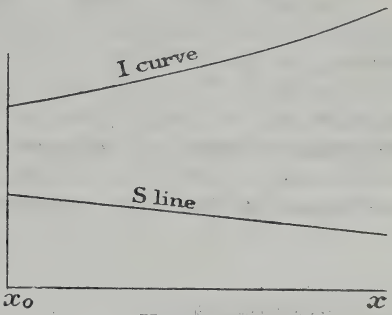


FIG. 267.

Again, it is found by experience that, for a rise of temperature $(x - x_0)$, the elastic moment S becomes $S[1 - \beta (x - x_0)]$, where β is a constant, so that S is diminished by a constant quantity $S\beta$ multiplied by the change of temperature. Therefore, if we plot S to a temperature base, the resulting graph will be a straight line as shown in Fig. 267, and it will be seen that the ratio of I to S, and consequently the time of oscillation is different at every temperature.

Now let us consider a balance wheel in which the rims are bimetallic as described in § 345. The coefficient of expansion of the outer metal (brass) is greater than that of the inner (steel), so that, when the temperature rises, the rims approach the centre of the wheel, and when it falls they recede from the centre. The result is that the moment of inertia of the balance increases or decreases according as the temperature falls or rises, which is the converse of what happens with the homogeneous balance.

Let x_0 be the temperature at which the rims are circular, and have their common centre in the axle of the wheel; then at temperatures above x_0 the rims curve inwards, while at temperatures below x_0 they curve outwards. At temperature x_0, I will be the same wherever the compensating masses may be on the rims, but at any temperature other than x_0, I will depend on the position of the compensating masses on the rims as well as on the temperature. It follows that there will be an I curve for every position of the compensating masses.

If we consider six positions of the compensating masses, say, close up, 30°, 60°, 90°, 120°, and 150°, reckoned from the fixed ends of the rims, the corresponding I curves will be as shown in Fig. 268, the curvature of each being opposite to that in Fig. 267.

From Fig. 268 it will be seen, that by placing the compensating masses at a particular angle (120° in this case), the ratios of I to S at temperatures x_1 and x_2 will be the same, and therefore the times of oscillation at those temperatures will be the same. Between these limits there will be a slight increase, and outside of them a decrease in the time of oscillation.

That which has been said above should be regarded as a rough explanation only, and it should be observed that, since

I and *S* are not of the same nature, it is not strictly accurate to speak of the ratio of *I* to *S*.

The fact that the times of oscillation can be made the same at any two temperatures, by suitably placing the compensating masses, is the principle of the thermal compensation of the chronometer. The two temperatures, 45° F. and 90° F. are selected as the limits likely to be experienced, and the compensating masses are adjusted by trial so that the times of oscillation at these two temperatures are the same, the time of oscillation at the mean temperature having first been found.

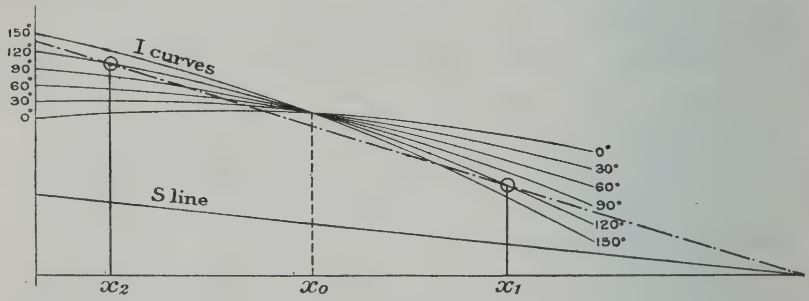


FIG. 268.

For example, suppose that the daily rate of a chronometer when subjected to a temperature of $67\frac{1}{2}$° F. was 4 seconds gaining, and that when subjected to a temperature of 45° F. and 90° F., the rates were 2 seconds and 7 seconds gaining respectively; then it is clear that the compensating masses are too close to the free ends of the rims, and must be moved towards the fixed ends, and so on, till the rates at the two temperatures are found to be the same.

When the compensating masses have been adjusted, it may be necessary to reduce the rate at the two limiting temperatures, and this is done by means of the screws l''.

It will be seen from Fig. 268 that, if the rate at the extreme temperatures is zero, the chronometer will lose slightly at intermediate temperatures, the maximum losing rate occurring at the middle temperature. The rate at the middle temperature is called the middle temperature error, and in a good chronometer should not exceed 2 seconds. Various forms of auxiliary compensation are applied to chronometer balances in order to reduce the middle temperature error, and the principles on which most of them are constructed are (1) to check the opening of the rims at low temperatures, (2) to cause an auxiliary weight to move inwards at high temperatures. During the past few years it has been found that the middle temperature error may be very much reduced, by replacing the steel of the balance by an alloy of iron and nickel, which belongs to the same series of alloys as invar. This alloy is almost non-magnetic. Up to the present time this alloy has been very little used in the construction of the chronometers which are supplied to H.M. Ships.

348. Testing of chronometers at the Royal Observatory.—Chronometers, before being purchased for use in the Royal Navy, are subjected to very severe tests at the Royal Observatory at Greenwich, in order to determine their performances at various temperatures. These tests extend over twenty-nine weeks and comprise observations of the rate at temperatures up to 98° F.

A considerable number of chronometers are tested together and, after the test, are tabulated in order of merit as shown by the formula $a + 2b$, where a is the difference between the greatest and least weekly rates, and b is the greatest difference between two consecutive weekly rates. For a considerable number of chronometers, the formula gives a result below 30, while for a few it is as small as 10, from which we see the high pitch of perfection to which the thermal compensation has been brought.

The limits, within which the daily rate of a chronometer should lie, before the chronometer is supplied to one of H.M. Ships, is given in the preface to the chronometer journal, which should be studied in this connection.

349. The formula for the rate.—With the compensation described in § 347, it is found that

$$R = R_1 + K(x - x_1)^2$$

in which R is the daily rate; x is the mean temperature during the day; R_1 is the daily rate when the temperature is x_1 and K is a constant. In the application of this formula x may be taken as the mean of the readings of the maximum and minimum thermometers (§§ 367, 368).

Experience shows that K and x_1 remain constant for a long period, but R_1 is liable to change, and should, therefore, be frequently verified.

Example.—A chronometer was found by observation to have a losing rate as follows:—

Rate	2·29 secs.	Temperature	50° F.
,,	·64 ,,	,,	65° F.
,,	·97 ,,	,,	80° F.

Required the formula for the rate, and the rate when the readings of the maximum and mimimum thermometers (for the day) are 76° and 70° respectively.

By substitution in the equation above we have

$$\begin{aligned} 2{\cdot}29 &= R_1 + Kx_1^2 - 100\,Kx_1 + 50^2\,K. \\ {\cdot}64 &= R_1 + Kx_1^2 - 130\,Kx_1 + 65^2\,K. \\ {\cdot}97 &= R_1 + Kx_1^2 - 160\,Kx_1 + 80^2\,K. \end{aligned}$$

Subtracting the second of these equations from the first and third we have

$$1{\cdot}65 = 30\,Kx_1 - 15 \times 115\,K,$$
$$\cdot 33 = -\,30\,Kx_1 + 15 \times 145\,K,$$

adding

$$1{\cdot}98 = 15 \times 30\,K;$$
$$\therefore K = \cdot 0044.$$

With this value of K it is easily found that

$$x_1 = 70^\circ \text{ F. and } R_1 = \cdot 53 \text{ secs.}$$

Therefore the formula for the rate is

$$R = \cdot 53 \text{ secs.} + \cdot 0044\,(x - 70^\circ)^2 \text{ secs.},$$

and when the temperature is 73°, which is the mean of the thermometer readings, we have

$$R = \cdot 53 \text{ secs.} + \cdot 0044 \times 9 \text{ secs.}$$
$$= \cdot 57 \text{ secs.}$$

350. Variation of the rate due to age.

350. Variation of the rate due to age.—The effect of age on a chronometer is to produce a change in the viscosity of the oil, a deposit of dirt on the various parts of the mechanism, and a slight wear between the moving parts. These tend to produce a slight acceleration.

To avoid the possibility of the oil evaporating, a deck watch should never be left exposed to the sun.

Chronometers should be sent to their makers at least every four years for repairs. The date of the last repair is given on a paper pasted on the lid of the wooden case. A chronometer, when four years have elapsed since the last repair, should be sent to the nearest chronometer depôt and another procured. Should it be necessary to send a chronometer by rail, the greatest care should be taken to guard against damage in transit. Full printed instructions as to the method of packing, &c., are issued to each ship in the chart set, and should be carefully followed.

351. Abnormal variations in the daily rate.—In spite of the compensation of a chronometer for temperature, variations in the rate, due to other causes, occur. These variations are due to—

(1) Atmospheric conditions.
(2) Magnetism.
(3) Motion of the ship.
(4) Damp.

Atmospheric Conditions.—It is found that dampness of the atmosphere causes a retardation, which may be accounted for by the increase of the moment of inertia of the balance due to a deposit of microscopic sediment.

Magnetism.—At the Royal Observatory at Greenwich, trials have recently been carried out, to determine the effect of a magnetic field on the rate of a chronometer, and it has been found, that a field in which the lines of force are parallel to the plane of the balance has the greatest effect, while a field in which the lines of force are vertical has practically no effect. It has also been found that the effect of the former field varies with the direction of the lines of force, as regards the XII. to VI. line of the dial; it was concluded that the variation of the rate was due to the magnetisation of the steel of the balance wheel, and that the magnetisation of the balance spring had no appreciable effect. Let us neglect the magnetisation of the steel of the rim of the balance wheel, and only consider that of the arm, which will first be supposed to lie along the lines of force when the wheel is in the position of equilibrium; it will be obvious that the arm, when displaced from this position, will be acted on by an additional couple which acts with the balance spring, and consequently lessens the time of oscillation. Now, suppose that the arm is at right angles to the lines of force when the wheel is in its position of equilibrium; in this position the arm is not magnetised, but, as soon as it deviates from this position, the field produces a couple, which acts against the balance spring and consequently lengthens the time of oscillation. Therefore, between these two positions, there must be one at which the time of oscillation of the balance is unaffected by the field. The above was borne out at the trials, when it was found that the rate was unaffected if the arm of the balance wheel, when in equilibrium, was at 45° to the lines of force.

The position selected for the chronometers on board ship, should be so far removed from magnetic influences, that the rate of the chronometer is unaffected. From the experiments mentioned above, it appears that a magnetic field of strength F dynes may change the daily rate of a chronometer by an amount, not exceeding

$$1{\cdot}35\,F^2 \text{ seconds.}$$

Now it may be assumed that the strength of the magnetic field of each of the various instruments mentioned in § 305, when at the distance tabulated under the heading "From Standard Compass Position," does not exceed half the earth's field, that is 0·09 dynes. As the strength of a magnetic field varies inversely as the cube of the distance, at a fraction K of the tabulated distance the strength of the field is

$$\frac{0{\cdot}09}{K^3} \text{ dynes.}$$

Therefore, due to this field the maximum change in the daily rate of a chronometer is

$$1{\cdot}35\left(\frac{0{\cdot}09}{K^3}\right)^2 \text{ seconds.}$$

If we equate this expression to one second, we find that

$$K = 0{\cdot}47$$

Therefore no instrument mentioned in § 305 should be brought within one-half the distance tabulated under the heading "From Standard Compass Position"; this rule being followed, the change in the daily rate, due to any one of these instruments, should be less than one second.

The correcting magnets and heeling error instrument should be as far away as possible, and the chronometer box should not be placed against an armoured bulkhead.

The effect of magnetism on the deck watch, which may have to be carried from one position in the ship to another, may be considerable, and experiments are now being carried out with a view to finding to what extent the deck watch is shielded from magnetic influences, by being kept in a soft iron box.

Motion of the ship.—It has been found that the rolling and pitching of the ship causes a very slight acceleration of the chronometer, and that shocks due to waves striking the ship, &c., cause a retardation. It has also been found that, as a rule, the rate is different according as the ship is under way or in harbour, the rate in the former case being called the sea or travelling rate and in the latter the harbour rate. Care should be taken that each chronometer is properly suspended in its gimbals, for if there is a small amount of play in the bearings the chronometer will experience shocks as the ship rolls or pitches.

Damp.—One of the greatest dangers to which a chronometer is liable on board ship is rust, which acts on the balance spring and alters its elasticity. Conditions, leading to a deposit of moisture on the chronometer, or "Sweating," should be carefully avoided, and any material, such as cotton waste, used to pack the chronometers in the box, should be perfectly dry. The danger is to a great extent avoided in the construction of the chronometer boxes which are supplied to modern ships; in these, as will be explained in § 353, springs are substituted for packing.

352. To wind and start a chronometer.—As will be understood from the above, in order that the daily rate of the chronometer may be as constant as possible, it is important that the interval, during which the motive power is transferred from the mainspring to the spring xy (§341), should be of the same duration each day; for this reason, chronometers should always be wound in the same manner and by the same person, and, although a particular chronometer may have been constructed to run for two or more days, it should be wound daily.

Again, in order that the same portion of the mainspring, chain and fusee may be in action on each day, the chronometer should be wound at the same hour.

A chronometer is wound by turning the key from right to left, the key, called a tipsy key, being so constructed that no couple is communicated to the fusee if it is turned in the wrong direction. When about to wind, the chronometer should be gently turned over in its gimbal ring until its face is downwards; it should then be held firmly by the left hand and the shutter moved to one side; the key should then be inserted by the right hand, and the winding performed gently and evenly till the mechanism is felt to butt, the instant being anticipated by counting the number of half-turns of the key which is known to be required. The key should then be withdrawn and the chronometer gently turned back to its original position, note being taken that the up and down indicator points to "wound." It is convenient to note the number of half-turns required on a piece of paper and to paste it in the lid of the box. The number of half-turns required daily for different chronometers are approximately as follows:—

One-day chronometer, 10 half-turns.
Two ,, ,, 7½ ,,
Eight ,, ,, 4 ,,

A one-day chronometer runs for about 30 hours, and a two-day for about 54 hours.

A deck watch, when being wound, should be held steadily in one hand, with the face downwards. It should not be oscillated in sympathy with the winding of the other hand.

It is advisable that the comparisons should be made at the same time as the chronometers are wound, and, to avoid forgetting any details, a regular system should be adopted; for example—wind the chronometers in turn, commencing from the left; then wind the deck watch or watches; note the readings of and reset the maximum and minimum thermometers; compare all chronometers and watches with the *A* chronometer as explained in § 140; work up the error of each chronometer from that of the previous day and deduce the error of the deck watch; note the error of the deck watch on a piece of paper placed inside the lid of its box.

In order to start a chronometer, the gimbals should be locked and the instrument held by the hands with its dial horizontal; it should then be given a quick turn in azimuth through about 90°, without any shake. This movement, on account of the inertia of the balance, will give a slight compression or tension to the balance spring, which should be sufficient to cause the balance to unlock the escape wheel and allow the mechanism to start.

If it is desired that the chronometer should show G.M.T., the instrument should be started at the correct time, rather than the hands should be moved; for example, suppose that the *C* chronometer has stopped, showing $4^h\ 10^m\ 27^s\cdot5$, and that the error of the *A* chronometer on G.M.T. is $2^h\ 19^m\ 11^s$ slow.

$$\begin{array}{lrrrl} \text{G.M.T.} & 4^h & 10^m & 27^s\cdot5 & \\ A & 2 & 19 & 11\cdot0 & \text{slow on G.M.T.} \\ \hline A\ \text{shows} & 1 & 51 & 16\cdot5 & \\ \hline \end{array}$$

In this case the *C* chronometer should be started when *A* shows $1^h\ 51^m\ 16^s\cdot5$ and this may be done by giving the turn to *C* about half a second before the above time is indicated by *A*.

On account of the possibility of straining the mechanism or bending the hands, it is inadvisable to set a chronometer to time by moving the hands.

353. The stowage and care of chronometers on board ship.—A special room, called the chronometer room, is selected for the stowage of chronometers, and is as far as possible removed from magnetic fields and not exposed to large variations of temperature. In the chronometer room is a box, called the chronometer box, in which the chronometers are kept. Specially prepared blocks of well-seasoned wood, about 2 feet high, are bolted to the deck; on the top of these is a sheet of india rubber, and on this sheet is a tray, divided into compartments for the reception of the chronometers. The interior of each compartment, at the sides and bottom, is provided with springs for holding the chronometer cases firmly in place. Fitting over the whole of the above, but not touching it, is a wooden casing, the lower edge of which is secured to the deck; this casing is fitted with two lids, each of which is provided with a lock, the inner being of glass and the outer of wood. Before the instruments are placed in the compartments the top lids of their cases are removed. The glass lid of the outer casing of the chronometer box is so arranged that, when it is closed, the glass lids of the chronometer cases are very close to it, so that the indications of the chronometers may be read without opening the glass lids or touching the instruments.

When it is necessary to move a chronometer, the greatest care should be taken to avoid disturbing its rate and possibly damaging its delicate mechanisms. In such a case the gimbals should always be locked and the instrument carried in both hands, great care being taken not to turn it in azimuth, for, should a turn happen to coincide with the direction of movement of the balance, the instrument may stop; should the turn coincide with the opposite direction to that of movement of the balance, the spring may be strained. If the chronometer is to be carried for some distance, it is advisable to place it in the padded guard case which is supplied with each instrument.

In armoured ships, in which the chronometer room is not situated behind the armour, a protected position is selected to which the chronometer box should be moved in time of war.

It is usual to place the *A* chronometer in the middle compartment of the chronometer box and the others on either side of it, because this facilitates comparison.

CHAPTER XXX.

VARIOUS INSTRUMENTS.

354. The patent log.—A patent log is an instrument for recording the distance run through the water. The principle embodied is that a small screw propeller (called the rotator), when towed through the water, makes a certain number of revolutions in a given distance and hence, by being attached to a mechanism (called the registering apparatus), registers the distance run through the water in a given time.

Various kinds of patent logs are in use in the Royal Navy, and that which will be here described is called the Trident Electric Log. The registering apparatus, two views of which are shown in Fig. 269, is fixed to the stern of the ship, while the rotator is in the water and connected by means of a long line to one extremity of the axle of a wheel, called the governor; the other extremity of the axle of the governor is connected by a short length of line to the registering apparatus.

The rotator communicates its motion to the eye *M*, at the end of the axle of the registering apparatus, which, in turn, by means of a reducing mechanism contained in the case *A*, communicates its motion to three pointers on the face. The case *A* is attached to the body of the instrument by four screws *B*. The body is supported by trunnions in a fork *C*, and this can revolve in the foot *D*, which fits into a shoe *E* secured to the ship. The pull of the rotator and line is taken, through ball-bearings, by a cap *F* screwed on to the end of the instrument. The ball-bearings are covered by a tube *G*, which may be revolved to allow the bearings to be oiled through a hole in it.

Fig. 270 shows the ball-bearings, axle and eye, which together can be detached from the instrument by unscrewing the cap. The bearings consist of two necklaces of balls which roll in V-grooves; the outer necklace receives the pull of the rotator and line, and the inner is for the purpose of adjustment and for keeping the axle steady. The balls and grooves are enclosed in a skeleton cage *N*, which can be unscrewed from the cap for cleaning or renewal. The adjustment of the bearings is effected by screwing up the cage cap *b*, which may be locked by a specially formed washer and the two screws *a*, *a*. Should the outer grooves become worn the whole cage and bearings may be reversed, and the pull of the line thus transferred to what was previously the inner and practically unused balls and groove.

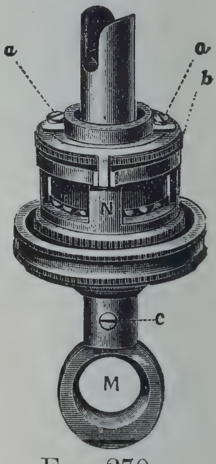


Fig. 270.

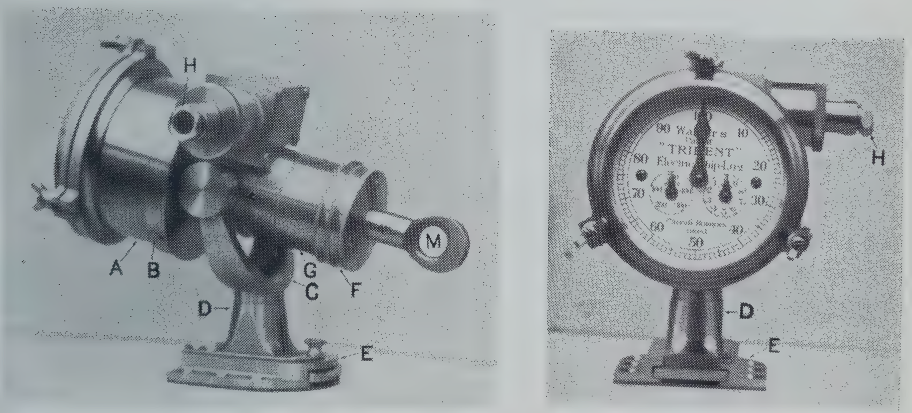


Fig. 269.

The electrical portion of the instrument consists of a make and break mechanism in the registering apparatus, and a receiver; the dial of the receiver is arranged in a similar manner to that of the registering apparatus, Fig. 269. The receiver is placed in the chart house and is connected by a permanent circuit to terminals at the stern of the ship; a watertight flexible lead from the terminals is connected to the registering apparatus at the watertight connection *H*. The make and break mechanism completes the circuit at every tenth of a mile as indicated by the instrument, and thus every movement of the hands of the registering apparatus are repeated on the receiver.

Care should be taken when handling the rotator that the blades are not damaged, for a blow may impair the accuracy of the instrument. When the log is to be used, the governor wheel should be attached to the registering apparatus by means of the eye *M* and the rotator put overboard, the hook on the inner end of the line being placed in the eye of the governor and the hands set to zero.

The accuracy of a patent log depends largely on its being used with a suitable length of line, and as this varies in different vessels, it is necessary to make some experiments at sea, when steaming over a known distance, so as to ascertain the best length for a particular vessel. The following lengths of line have been found to be suitable for normal vessels :—

Maximum speed	10 knots.	Length of line	40 fathoms.
,, ,,	15 ,,	,, ,,	50 to 55 fathoms.
,, ,,	18 ,,	,, ,,	60 ,, 65 ,,
,, ,,	20 ,,	,, ,,	70 ,, 80 ,,
,, ,,	25 ,,	,, ,,	100 ,, 120 ,,

Should the above not give accurate results, lengthening the line will generally be found to increase the log registration, and *vice versâ*. For small high speed vessels, such as Torpedo Boat Destroyers, shorter lines may be used than those given above. The length of line, when found to be correct, should be adhered to, and new lines, which stretch considerably, should be shortened as measurements may indicate. It is better to use a line which is too long than one too short, because with a longer line the rotator is deeper in the water and the log is less affected by rough weather.

355. The speed by steaming over a measured distance.—The speed of a ship is found by steaming over a measured distance, and for this purpose beacons are set up at various places along the coast. In Fig. 271, *A*, *A′* and *B*, *B′* are two pairs of beacons, such that *AA′* is parallel to *BB′*, and the distance between these lines is exactly known. The ship whose speed is to be ascertained steams at right angles to these lines and notes the time when *A′* and *B′* are in transit with A and B respectively, the speed of the engines being kept uniform. The distance and time being known, the speed may be easily found.

If a tidal stream or current exists, the ship should steam over the measured distance in both directions, and her speeds with and against the stream should be ascertained; her speed through the water is then the mean of these speeds.

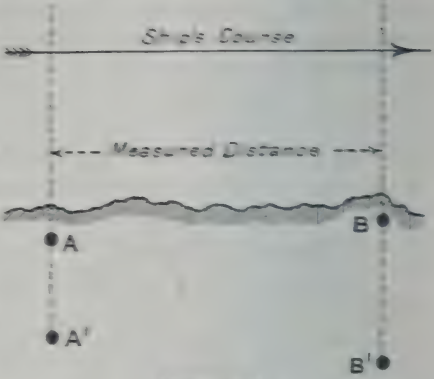


Fig. 271.

356. The error of a patent log.—Patent logs do not always correctly register the distance run through the water. The error of a patent log should be recorded as a percentage of the distance which the log actually shows, and not as a percentage of the distance run. This error may be found in either of the two following ways, the second of which is to be preferred, as being the more accurate :—

(1) By noting the readings of the patent log on two occasions of fixing the ship's position. The distance run over the ground may be taken from the chart and, due allowance having been made for the effect of the tidal stream or current, the distance run through the water may be obtained and compared with the distance shown by the log.

(2) From runs over a measured distance, with and against the tidal stream.

Example of (2).—A ship steamed at a uniform speed between the transit lines (8,678 feet apart) given by the beacons in West Bay, Portland, and the following observations were taken :—

		D.W.	Patent log.
Against the tidal stream	A φ A'	4h 34m 16s	39·5 miles
	B φ B'	4 40 45	41·2 „
With the tidal stream	B φ B'	4 56 27	42·9 miles
	A φ A'	5 02 04	44·2 „

The run against the tidal stream gives a speed of 8,678 feet in 389 seconds; that is, 12·91 knots.

The run with the tidal stream gives a speed of 8,678 feet in 337 seconds; that is, 15·25 knots.

The mean of these speeds is 14·08 knots, which is the speed of the ship over the ground.

Now the patent log gives a speed of 3 miles (1·7 + 1·3) in 726 seconds; that is, 14·88 knots. Therefore the speed of the ship as found by the patent log is too great by ·8 knots in 14·88; the error of the patent log is, therefore, 5·37 per cent. overlogging.

When finding the error of a patent log from the indications of a chart house receiver, it should be borne in mind that the pointer of this instrument only indicates every tenth of a mile. In order to find what the patent log showed at the instant of the transit coming on, it is necessary to note the times at which the electric impulses, immediately preceding and succeeding the transit, were received as well as that of the transit; the reading of the patent log at the time of the transit may then be found by interpolation.

357. The speed by the revolutions of the engines.—The number of revolutions per minute at which the engines are working provides a ready and, under ordinary circumstances, an accurate method of obtaining the speed of the ship. A tabular statement showing the speed of the ship in smooth water, when at her normal draught and with a clean bottom, corresponding to various speeds of the engines, is made out for each ship from actual trials; from this statement the speed of the ship may be estimated. It must not be expected that this method will give correct results when the ship's bottom has become foul, and therefore an allowance should be made, obtained from experience, depending on the interval which has elapsed since the ship was docked. Again, when steaming against a head sea, the speed developed will be less than that tabulated, and therefore under such circumstances it is difficult to estimate the speed of the ship from the revolutions of the engines.

358. The sounding machine.—A sounding machine is an instrument with which to ascertain the depth of water at any place. The type of sounding machine in general use in the Royal Navy is that known as the Kelvin Mark IV, which may be worked either by hand or by electric motor.

Fig. 272 shows the Mark IV. hand machine, which consists of a framework supporting a drum on a horizontal axle, the drum being wound with 300 fathoms of 7-strand flexible steel wire. The drum is free to revolve on its axle or may be gripped to the sprocket wheel by means of wooden brake-cheeks actuated by the handles. Thus, the sprocket wheel having been fixed to the frame by means of the brake catch-pin, a turn of the handles in the direction in which the wire runs out will free the drum; a turn of the handles in the opposite direction will grip the drum to the sprocket wheel, and, if the brake catch-pin be withdrawn, the drum and sprocket wheel may be revolved by turning the handles. 11

On the left face of the drum is a V-shaped groove, in which rests the automatic brake cord, on the inner end of which is a 6-lb. weight working in a vertical tube, and on the outer end a 1-lb. weight. The object of the automatic brake is to ensure that, when the wire is running out, the drum revolves at a uniform speed, and to prevent the drum over-running when the lead reaches the bottom. On the top of the frame is a pointer, which is connected by gearing to the drum, and indicates on a horizontal dial the number of fathoms of wire that have run out. When the ship is steaming above 13 knots, it is sometimes found that the 6-lb. weight is liable to jump out of its tube, and for this reason four 1-lb. weights, shaped so as to exactly fit over the former, are provided, one or more of which may be added as necessary.

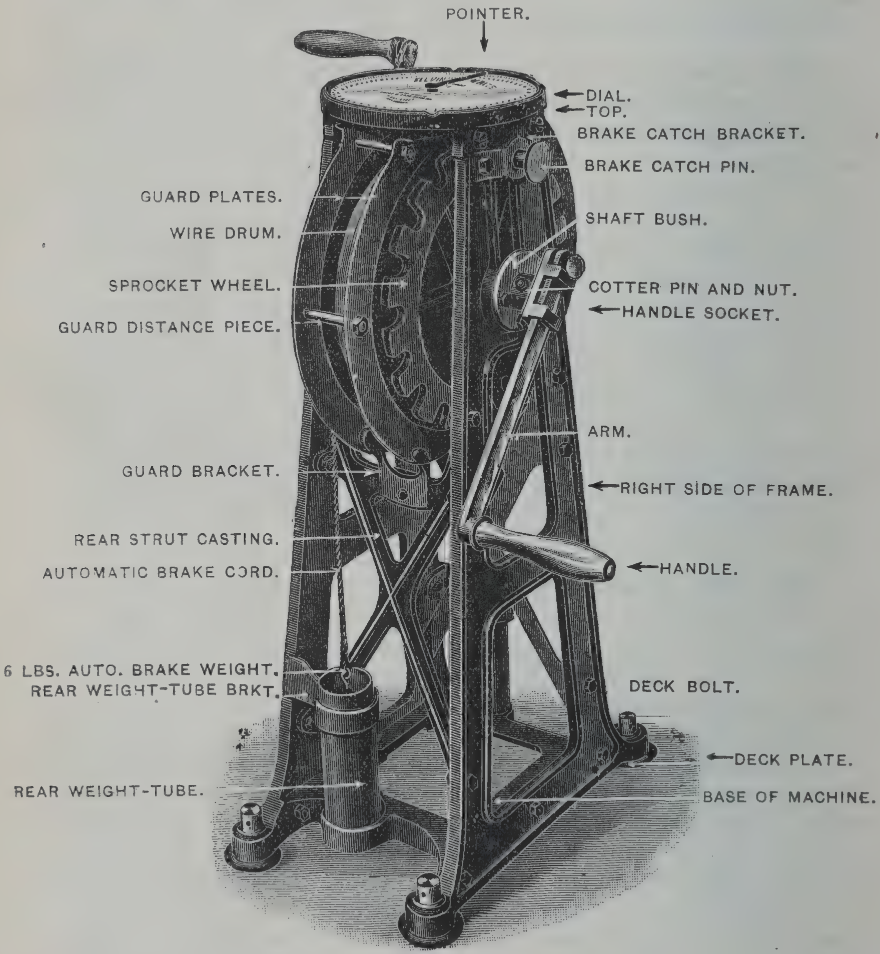


Fig. 272.

On the end of the wire is a swivel, to which is attached 9 feet of plaited hemp, called the stray line, at the extremity of which is secured the lead which weighs 24 lbs. Attached to the stray line, about 6 feet above the bottom of the lead, is a brass tube, called a guard tube, the upper end of which is fitted with a cap with a bayonet joint, the lower end having holes in it to freely admit the water. The use of this guard tube will be understood later.

The sounding machine is usually mounted in the fore part of the ship, and generally in such a position that it is visible from the bridge. The wire is led from the machine through a special swivel block carried on a traveller at the end of a spar, 30 to to 40 feet long, which projects horizontally from the ship's side.

The wire of the sounding machine having been snatched in the block, and the latter on its traveller having been hauled to the end of the spar by means of an outhaul, the lead should be lowered until it is just clear of the water, and this may be done by withdrawing the brake catch-pin and revolving the drum by means of the handles. When the lead is at the required position, the brake catch-pin should be re-inserted and the pointer set to the zero of the scale. If the ship is at rest, the depth may be easily obtained by allowing the wire to run out, and noting the reading of the pointer when the lead strikes the bottom, the instant being easily detected by means of a feeler pressed on the wire. When the ship is under way it is impossible to obtain an up and down cast of the lead, and hence the depth by direct measurement; for this reason, one of two indirect methods are employed, which will be now described.

359. The depth by chemical tube.—A glass tube, the inside of which is lined with chloride of silver (coloured red), one end being open and the other sealed, is inserted in the guard tube with its open end downwards; then, as the lead descends, the water is forced up the tube, and the air within the tube compressed. The salt water, as far as it rises, turns the chloride of silver white; therefore the height to which the water rose in the tube at the greatest depth is known; from this height the depth may be found as follows.

Let h (Fig. 273) be the length of the inside of the tube and x the height the water rises in the tube. Let p be the atmospheric pressure, and p' the pressure of the air in the tube when at a depth d, then, from Boyle's law, we have

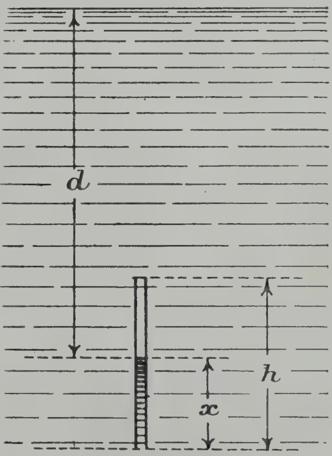


FIG. 273.

$$\frac{p'}{p} = \frac{h}{h-x}.$$

Now $p' = wd + p$, where w is the weight of sea-water per unit volume.

Therefore $$\frac{wd + p}{p} = \frac{h}{h - x},$$

$$\therefore \quad d = \frac{px}{w(h - x)}.$$

Now the weight of a cubic inch of mercury is ·49 lb., so that, if H is the height of the barometer in inches,

$$p = \cdot 49\ H\ \frac{\text{lb.}}{\text{inch}^2}.$$

The specific gravity of sea-water is 1·025, and as a cubic foot of fresh water weighs 62½ lbs.,

$$w = \frac{1}{27}\ \frac{\text{lb.}}{\text{inch}^3}.$$

Therefore, substituting these values for p and w, we have

$$d = 13 \cdot 23\ H \left(\frac{x}{h - x}\right) \text{ inches}$$

$$= \cdot 1837\ H \left(\frac{x}{h - x}\right) \text{ fathoms.}$$

From this we see that the depth depends on the height of the barometer and that it increases very fast as x approaches h. To avoid the necessity of calculation, a boxwood scale is graduated to show d for various heights (x) of water in the tube; by placing this scale alongside the tube, the depth can be read off.

The boxwood scale is fitted with a brass projection at one end, and when using it the tube should be in contact with the scale and with its sealed end against the brass projection. The scale is so adjusted that no appreciable error is introduced when the height of the barometer is between 28¾ and 29½ inches, but when it is above this height a correction must be applied as follows :--

Barometer	29·75.	Add one fathom	in	40.
,,	30·00.	,,	,,	30.
,,	30·50.	,,	,,	20.
,,	31·00.	,,	,,	15.

The temperature of the tube, at the instant it is immersed, should be the same as that of the sea water, because a change in the temperature of the tube will change the pressure of the air inside the tube and vitiate the reading. In order to ensure that the temperature of the tube is the same as that of the sea water, the tube should, for a few minutes before being used, be partially immersed, sealed end downwards, in a bucket of freshly drawn sea water. When a tube has been brought to the proper temperature before being used, the whole volume of water forced into the tube, when at its lowest depth, will be expelled by the compressed air on the tube being brought to the surface. If, however, due to the above precaution having been omitted, the tube was warmer than the water, a small quantity of water will be found inside the tube after it has been removed from the brass guard tube.

In order to ensure that the mark in the tube which indicates the height to which the water rose, usually referred to as the cut, may be regular and definite, the following points should be attended to :—

(1) The wire should not be allowed to over-run after the sinker has touched the bottom. Should a considerable amount of over-run be permitted, the tube may lie horizontally on the sea bed and the water tend to flow up the tube and cause a bad cut.

(2) The brakes of the sounding machine should not be applied too suddenly. Should the running out of the wire be stopped with a violent jerk, the sinker, being at the end of a long line of steel wire, will oscillate and cause the water inside the tube to jump and make a bad cut.

(3) The guard tube and chemical tube must be held vertically until the depth has been read off on the scale.

If, from any cause, the cut is found to be irregular, the reading should be taken to the lowest part of the cut.

The tubes are supplied in hermetically sealed tins, 10 in a tin and 10 tins in a wooden box. It is important that the tubes should be kept free from damp and not exposed to the light, in order to preserve the chloride of silver from deterioration. For this reason a tube, when it has been used, should not be replaced in a tin in which there may be new tubes. Should a tube have deteriorated through age or neglect of the above precautions, it will usually appear of rather darker colour and more opaque.

360. Change of depth by the number of fathoms of wire run out.—On account of the regular rate at which the wire runs out, due to the action of the automatic brake, any large change in the depth of water at successive soundings is immediately apparent, on the lead reaching the bottom, if the reading of the dial is noted on each occasion. This method of noting a change in the depth of water is particularly valuable, because it gives an earlier indication that the ship is approaching shallower water than is obtained by the subsequent measurement of the chemical tube. For this reason, the men who work the sounding machine should be instructed to immediately report any large decrease in the number of fathoms of wire run out between successive soundings.

It is found, when the precautions, which are enumerated below, are complied with, that for a particular speed of the ship, the depth of water bears a more or less constant relation to the number of fathoms of wire run out, and therefore it is possible to construct a table for a particular sounding machine, which shows the amount of wire required for the lead to reach the bottom, corresponding to various depths and speeds of the ship. Such tables, constructed for sounding machines in perfect adjustment, are supplied to H.M. Ships. As it is unlikely that all machines are identical, the table should be checked before being used by comparing the amount of wire run out with the depths obtained with chemical tubes at various depths and for various speeds. The depth of water should not, in general, be obtained by means of these tables, but a chemical tube should be used at each sounding, except as explained in the following article.

In order to ensure that the proportion between the depth and the number of fathoms of wire run out should be as constant as possible for any given speed of the ship, the following points should be attended to—

(*a*) When releasing the main brake, which should have been previously eased, at the order "Let go" the handle is given one complete turn in the contrary direction to heaving in; this should be done smartly.

(*b*) Sinkers of the same shape and of exactly the same weight should always be used.

(*c*) The same length and size of stray line should always be used, the swivels should be identical and the guard tube seized on in the same place.

(*d*) The same brake weight should be in use, because at a given speed, a heavier weight would not allow the wire to run out as fast as a 6-lb. weight.

361. How to take soundings.—The wire having been snatched in the block, insert the chemical tube in the guard tube, with its sealed end uppermost. Arm the lead, that is, fill a small cavity in its base with soap, in order that a sample of the bottom may be obtained. Haul the traveller to the end of the spar, and lower the lead to the water's edge, easing off the wire by means of the handles while doing so, then the brake catch-pin should be reinserted and the pointer set to zero. Ease up the main brake until the wire is just about to run out. Holding one of the handles in one hand and the brass feeler in the other, gently press the feeler on the wire, and, having noted the exact position of the handle, give it exactly one turn in the direction of running out. The wire will now run out, and a man should be stationed to note the exact reading of the dial at the instant the lead reaches the bottom, which is detected by the slackening of the wire under the pressure of the feeler; the handle should now be turned in the direction of heaving in, and this will apply the brake and stop the wire. This application of the brake should be made gradually and evenly and not violently (§ 359). The brake catch-pin may now be withdrawn and the wire hove in, being guided on to the drum through a piece of oiled canvas. When the lead is clear of the water the outhaul may be eased, when the continued reeling in of the wire will bring the traveller into the ship's side, and the chemical tube may be removed and compared with the scale. The base of the lead should now be examined in order to determine the nature of the bottom.

A book, called the sounding-book, is provided, and all information relating to soundings taken should be entered in it. As one of the data entered in the book is the speed of the ship, an inspection will show whether the table for sounding without the tubes is correct. When sounding at frequent intervals it is unnecessary to use a chemical tube on each occasion if the depths are regular, but if one is used at about every sixth cast of the lead, the depth at the intermediate casts may be inferred from the amount of wire run out.

The spars, or sounding booms, should always be rigged in place when under weigh, and soundings should be taken continually when in pilotage waters. It is advisable that the sounding party should be instructed to sound at certain regular intervals as indicated by the clock, for, should it be necessary to estimate the ship's position by plotting the soundings on tracing-paper (§ 67), the work is much simplified.

Sounding machines are generally placed on either side of the ship and, when it is necessary to obtain soundings with great rapidity, it is advisable to have two sounding parties, and to work the machines alternately. When steaming in 20 fathoms at a speed of 10 knots, soundings can be continuously taken with one machine at the rate of one a minute.

When the machine is not in use the main brake should never be left set up.

The principle of the action and the method of working the sounding machine which is driven by an electric motor, are similar to what has been described above, with the following exception:—

On the left of the machine is a skeleton wheel, keyed to the shaft, and, when taking a sounding, this wheel is turned through one revolution to release the drum in the same way, as the handle of the hand-worked machine. On the lead striking the bottom the switch of the motor is put over about half-way, when the motor puts on the main brake and commences to heave in the wire. The switch should now be gradually put over to the "on" position, when the wire will be hauled in at full speed. While heaving in, a careful watch should be kept on the indications of the dial; the motor switch should be eased up gradually when the pointer shows 10 fathoms, in order that it may be possible to stop heaving in the wire at the correct time. Should the motor be out of order, handles may be shipped and the machine used as a hand machine.

362. The station pointer.—The station pointer, Fig. 274, consists of a graduated circle and three arms, the chamfered edges of the latter radiating from the centre of the circle. One leg *OA* is fixed and its chamfered edge corresponds to the zero of the graduations of the circle, which are marked at every half degree from 0° to 180° on either side of the zero. The two legs *OB* and *OC*, called the left and right legs, may be revolved about the centre *O* and clamped in any position. The settings of their indices on the graduations indicate their respective inclinations to the centre leg.

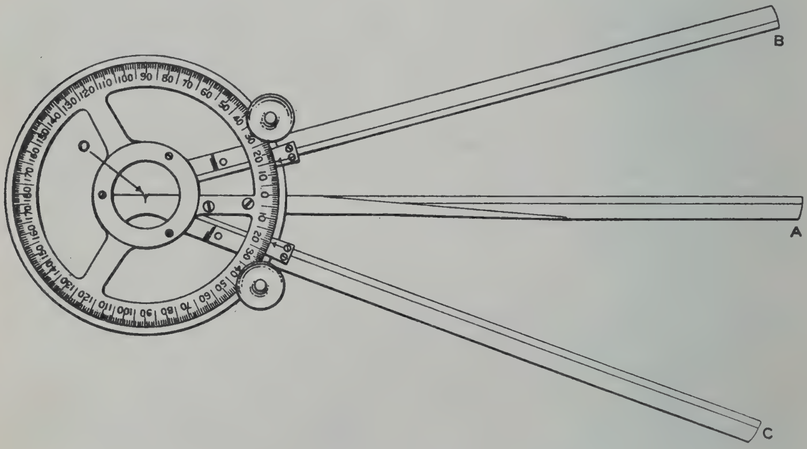


Fig. 274.

The centre of the circle is indicated by a small nick in the chamfered edge of the fixed leg, and, when using the instrument, a very sharp pencil point should be used, in order that the mark made on the chart may exactly correspond with the centre of the instrument which is on the continuation of the edge of the fixed leg.

The champhered edge of the right leg cannot be brought very close to that of the centre leg; for this reason when the right-hand angle is very small, and consequently the right leg cannot be set to it, the left leg should be set to the small angle; the right leg should be moved round and set to the sum of the right and left angles measured from the fixed leg to the left. Under these circumstances the fixed leg should be directed to the right-hand object.

To check the accuracy of the instrument, radiating lines should be ruled on a sheet of paper, the angle between adjacent lines being 10°, and laid off by the method of chords. The instrument should be placed on the paper with the nick exactly at the centre of the radiating lines, and with the chamfered edge of the fixed leg coincident with one of them. Weights should be placed on the instrument to prevent it from being accidentally moved, and the right and left legs should then be successively placed so as to coincide with the lines, and the readings of the scale ascertained. The errors corresponding to the various angles, marked + or − according as they should be applied to an observed angle, should be tabulated and pasted in the lid of the box. While testing the instrument it should be noted whether the chamfered edge of each leg coincides throughout its whole length with one of the straight lines.

363. The marine barometer.—The barometers used on board ship are of three kinds—the marine barometer, the aneroid and the barograph.

The marine barometer is a special type of mercurial barometer, which latter, in its simplest form, is merely a glass tube closed at one end and filled with mercury, the tube and mercury having been boiled in order to extract any minute particles of air which may adhere to the sides of the glass; the tube is inverted and its open end placed below the level of the surface of the mercury contained in a small cistern. The mercury now descends in the tube until the weight of the column is balanced by the pressure of the atmosphere on the mercury in the cistern. By means of a scale of inches, whose zero is level with the surface of the mercury in the cistern, the exact height of the column may be recorded. Certain corrections have to be made to the reading as shown by such a barometer, in order that comparisons may be made with other barometrical observations. The necessities for these corrections are as follows:—

(1) *Capacity.*—When the barometer scale is fixed, its zero is level with the surface of the mercury in the cistern at one particular pressure only. When the pressure decreases, the mercury in the tube drops and flows into the cistern, where it raises the level; the reading is now too high, since the zero of the scale is below the surface of the mercury in the cistern; the converse occurs when the pressure increases.

(2) *Capillarity.*—This correction is made necessary by the affinity of the mercury for the interior surface of the tube, which lowers the level at the edge and gives a curved form to the top of the mercury column.

(3) *Temperature.*—As the temperature rises or falls, so does the volume of mercury increase or diminish, so that to make comparison possible a certain fixed temperature, to which all readings may be reduced, must be selected.

(4) *Height.*—The pressure of the atmosphere is a maximum at the sea-level and decreases with the height therefrom, so that to make comparison possible a certain level has to be selected.

(5) *Latitude.*—The weight of a column of mercury increases from the equator to either pole, so that it is necessary for some latitude to be agreed upon as the standard latitude at which weight is measured.

The marine barometer, Fig. 275, consists of a glass tube mounted in a metal case, at the bottom of which is a cistern; the mercury tube is exposed to view at the top in order that the level of the mercury may be read off by means of a brass scale and vernier, the latter being constructed to read to ·01 of an inch and in some cases to ·005 of an inch, and being adjusted by means of the milled head *D*.

Between the cistern and the scale an air-trap *A* is fitted, so as to catch any particles of air which may creep up the inside of the glass tube. There is a small hole *H* in the top of the cistern, which allows the atmosphere free access to the surface of the mercury. When the instrument is laid down, or inverted, the mercury is prevented from escaping through this hole by means of a leather valve.

The bore of the tube is contracted for the greater part of its length for the purpose of giving the tube greater strength and reducing the weight, and it is further contracted as shown at *C*, in order to prevent an up and down motion of the mercury (called pumping) due to the rolling and pitching of the ship; this contraction increases the friction of the mercury in the tube and consequently the marine barometer is somewhat slow in recording changes of pressure.

The instrument is supported in gimbals carried on a spring bracket, which is secured to a bulkhead.

The instrument should be placed in a carefully selected position, which should be, if possible, near the centre of gravity of the ship, away from traffic and in a uniform temperature.

When it is necessary to remove the barometer from the bulkhead, as, for example, when it has to be packed or when guns are being fired, the instrument should be inclined in order that the mercury may fill the space which is ordinarily a vacuum, and so be unable to impinge on the top of the tube. The process should be carried out very slowly because, as the instrument is inclined, the pressure of the atmosphere drives the mercury up the tube, and the impact on the top of the tube may cause breakage. The instrument, when removed from the bulkhead, should be kept with the cistern end above the level of the top of the tube. The handle of the barometer box is so fitted that, when the instrument is being carried in the box, the cistern end is slightly elevated.

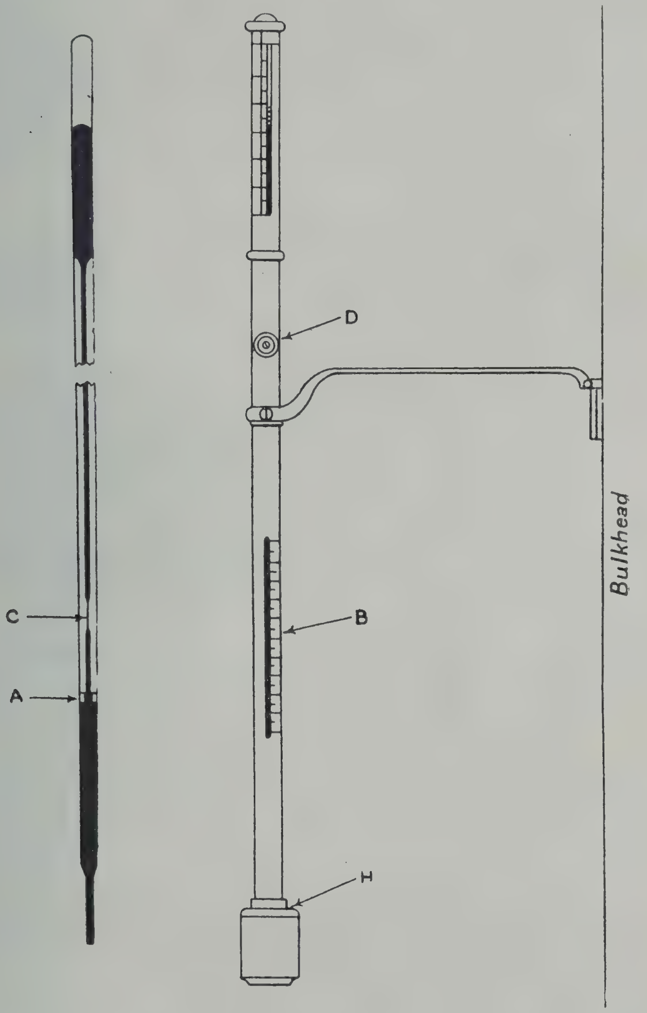


Fig. 275.

The various errors enumerated above are eliminated or allowed for in the marine barometer as follows:—

(1) *Capacity.*—This is eliminated in the graduation of the scale by means of what are known as "equivalent inches," the inch readings being made shorter than true inches; for example, if the area of the cistern is 24 times the area of the upper part of the tube where the variation in level takes place, for a change of barometric pressure of 1 inch the column rises or

falls $\frac{24}{25}$ths of an inch while the surface in the cistern falls or rises $\frac{1}{25}$th of an inch, and, as the zero of the scale cannot be altered, the divisions marked on the scale as inches must be really $\frac{24}{25}$th inch.

(2) *Capillarity.*—A correction for this error is permanently made by cutting off a small amount from the bottom of the scale. In this connection it may be remarked that, when reading the instrument, the zero of the vernier should always be made to coincide with the highest part of the curved surface of the mercury column.

(3) *Temperature.*—The temperature selected is that of the freezing point of distilled water, namely, 32° F. Attached to the side of the marine barometer is a thermometer *B*, Fig. 275, and in order that all readings of the barometer may be of value to the Meteorological Office in the construction and correction of isobaric charts, the reading of this attached thermometer should be taken and noted at each observation. A table for the correction is given in the Barometer Manual, reference to which shows that the correction is zero when the temperature is 28° F.; this is so because a correction for the expansion or contraction of the brass scale is included in the table.

(4) *Height.*—The level of the sea has been selected as the standard level, so that when comparing the readings of two barometers, the corrections due to their respective heights should be added to each. The decrease of atmospheric pressure is ·001 of an inch of mercury for every foot above sea-level. The height, at which the barometer is placed on board, should be entered on the first page of the ship's log for the information of the Meteorological Office.

(5) *Latitude.*—The latitude of 45° has been selected as the standard, and a table for reduction to this latitude is given in the Barometer Manual.

The heights of the barometer and attached thermometer should be observed and recorded in the ship's log every four hours; in unsettled weather additional observations should be taken.

364. The aneroid barometer.—The aneroid barometer depends for its indications on the movement of the top of a thin corrugated metal drum, which is partially exhausted of air so as to make it very susceptible to slight changes of external pressure. The top is connected to a pointer by means of a delicate mechanism which greatly magnifies its movement. The pointer can be set to indicate any particular pressure by means of a screw at the back of the instrument, and as the mechanism is liable to derangement, the reading of the instrument should frequently be compared with that of the mercurial barometer. If any difference is found, the aneroid should be adjusted to correspond with the mercurial barometer. The great advantages of the aneroid barometer are its convenient size, and the rapidity with which it shows any change of atmospheric pressure.

365. The barograph.—A barograph is an aneroid barometer provided with a lever which records variation of pressure on a revolving drum. It is in some respects a more valuable supplement to the marine barometer than the aneroid of the ordinary form. It is not only useful in enabling an observer to detect casual errors in the readings of the marine barometer, but also gives a continuous record of barometric pressure for reference. Barographs, moreover, register minor fluctuations of atmospheric pressure which are seldom noticeable in the action of the mercurial barometer. The instrument should be secured, or suspended, in a position where it is least likely to be affected by concussion, vibration or the movements of the ship.

The drum is driven by clockwork and makes one revolution in seven days. The paper forms, which fit on the drum, are graduated so as to show the day and time of day, as well as the height of the barometer in inches; a part of a specimen is shown in Fig. 164. Means are provided for adjusting the pen point so that it corresponds with the reading of the marine barometer, and a lever enables the pen to be withdrawn from the paper while the instrument is being moved, or during the firing of guns.

366. Thermometers.—Besides the thermometer used for taking the temperature of the sea-water, which should be observed every four hours when the ship is under way, two thermometers are kept mounted side by side in a wooden screen. One of these is fitted with a single thickness of fine muslin or cambric, fastened tightly round the bulb, and this coating is kept damp by means of a few strands of cotton wick. These strands are passed round the glass stem, close to the bulb, so as to touch the muslin and have their lower ends in a bowl of water placed close to the thermometer. This thermometer usually shows a lower temperature than the other, and the difference, commonly called the depression of the wet bulb, depends on the degree of dryness of the air. Such a combination is called a hygrometer, and a thermometer fitted as above is called a wet bulb thermometer, to distinguish it from the ordinary thermometer, which has its bulb uncovered and is known as the dry bulb thermometer.

The depression of the wet bulb thermometer is caused by the evaporation from the moistened covering of the bulb. When the humidity of the atmosphere is very great, during or just before rain, or when fog is prevalent or dew is forming, there is little or no evaporation, and the readings of the two thermometers are very nearly the same; at other times the wet bulb thermometer gives a lower reading than the dry, because the water evaporates from the muslin, and in the process of passing into the state of invisible vapour, it absorbs heat from the mercury in the bulb with the result that a lower temperature is indicated. As the air becomes less humid, the evaporation is greater, and the fall of temperature of the wet bulb is also greater; accordingly the difference of reading between the dry and wet bulbs is then also greater. The difference sometimes amounts to 15° or 20° F. in England, and more in some other parts of the world; but at sea the difference seldom exceeds 10°.

The accuracy of the record of the humidity of the air depends greatly on the precautions taken to ensure cleanliness, and on the provision of a proper supply of fresh water. It should be remembered that the observations are rendered faulty by the presence of salt water or dirt on the muslin or in the water. During frost, when the muslin is frozen, observations may still be taken, because evaporation takes place from ice as freely as from water. The reading of the hygrometer should be observed and recorded in the ship's log every four hours.

367. The maximum thermometer.—This instrument is provided for recording the maximum temperature of the air in the chronometer box during each day. It differs from an ordinary thermometer in that the zero is at the end of the tube furthest away from the bulb, and it has a small contraction in the bore just above the bulb, the effect of which is to increase the friction set up between the mercury and the glass, and therefore to prevent any passage of mercury unless it is under considerable pressure. Its action depends on the difference between the frictional resistance offered by the contraction of the bore and the combined forces of gravity and expansion of the mercury due to increase of temperature, the two last named being largely in excess of the first. When the instrument is suspended vertically, its bulb uppermost, the mercury in the bulb remains there if the temperature remains uniform, because the force of gravity is not sufficient to overcome the friction at the contraction. If the temperature decreases, the mercury still does not move, but a small space is formed in the bulb due to the contraction of the mercury. On the other hand if the temperature increases, the mercury expands and the surplus portion is forced through the contraction and falls to the bottom of the bore, which it fills by an amount which depends on the rise in temperature.

Thus the height of the mercury in the bore of the tube gives a record of the maximum temperature reached since the instrument was last set, and may be read off on the scale.

The mercury which has been forced through the contraction may not fall to the bottom of the tube, but may adhere to the side. In this case the thermometer should be inverted and the two portions of mercury allowed to join and move together to the bottom of the tube.

To reset, swing the instrument with the bulb downwards; the mercury at the bottom of the bore, under the influence of centrifugal force and gravity, is then able to overcome the resistance of the contraction and to refill the bulb. After being reset and suspended, bulb uppermost, the instrument should indicate the temperature at the time.

The maximum thermometer should be read and reset every day when the chronometers are wound and compared, and the reading should be entered in the chronometer journal.

368. The minimum thermometer.—This instrument is provided for recording the minimum temperature of the air in the chronometer box during each day. It differs from an ordinary thermometer in that alcohol, on account of its transparency and low freezing point, is substituted for mercury. A small black glass index, shaped like a dumbbell, is inserted in the column of liquid in the bore of the tube, and the action of the instrument depends on the movement of this index, which results from its being unable to break through the surface of the liquid.

The tube is kept in a horizontal position, and when the temperature rises the index remains stationary, and the liquid flows past it along the bore; but if the temperature falls, the index is carried towards the bulb as soon as the surface of the liquid touches it, and this movement continues until the temperature ceases to fall. Thus the position of the index gives a record of the minimum temperature reached since the instrument was last set, and may be read off on the scale.

Sometimes a division occurs in the spirit due to a fall or shake; to clear this the thermometer should be held, bulb downwards, and shaken vigorously.

To reset, the instrument should be held with the bulb uppermost; the index will then slide down till one end encounters the surface of the liquid, through which it will be unable to break

The minimum thermometer should be read and reset every day when the chronometers are wound and compared, and the reading should be entered in the chronometer journal.

APPENDIX A.

EXTRACTS FROM ABRIDGED NAUTICAL ALMANAC, 1914.

MARCH, 1914.

AT GREENWICH MEAN NOON.

THE SUN.

Date.		Declination.	Var. in 1 hour.	Semi-diameter.	Equation of Time *Add to Apparent Time.*	Var. in 1 hour.	Right Ascension of the Mean Sun (*Sidereal Time*).
		° ′	′	′ ″	m s	s	h m s
Sun.	**1**	S. 7 47·7	0·95	16 10	12 38·5	0·48	22 33 47·0
Mon.	**2**	7 24·9	0·95	16 10	12 26·8	0·50	22 37 43·6
Tues.	**3**	7 2·0	0·96	16 9	12 14·5	0·52	22 41 40·1
Wed.	**4**	S. 6 39·0	0·96	16 9	12 1·8	0·54	22 45 36·7
Thur.	**5**	6 15·9	0·96	16 9	11 48·6	0·56	22 49 33·3
Frid.	**6**	5 52·7	0·97	16 9	11 34·9	0·58	22 53 29·8
Sat.	**7**	S. 5 29·5	0·97	16 8	11 20·8	0·60	22 57 26·4
Sun.	**8**	5 6·2	0·97	16 8	11 6·2	0·61	23 1 22·9
Mon.	**9**	4 42·8	0·98	16 8	10 51·3	0·63	23 5 19·5
Tues.	**10**	S. 4 19·3	0·98	16 8	10 36·0	0·65	23 9 16·0
Wed.	**11**	3 55·8	0·98	16 7	10 20·3	0·66	23 13 12·6
Thur.	**12**	3 32·3	0·98	16 7	10 4·3	0·67	23 17 9·1
Frid.	**13**	S. 3 8·7	0·98	16 7	9 48·0	0·69	23 21 5·7
Sat.	**14**	2 45·1	0·98	16 7	9 31·4	0·70	23 25 2·2
Sun.	**15**	2 21·4	0·99	16 6	9 14·5	0·71	23 28 58·8
Mon.	**16**	S. 1 57·8	0·99	16 6	8 57·5	0·72	23 32 55·4
Tues.	**17**	1 34·1	0·99	16 6	8 40·2	0·72	23 36 51·9
Wed.	**18**	1 10·3	0·99	16 5	8 22·7	0·73	23 40 48·5
Thur.	**19**	S. 0 46·6	0·99	16 5	8 5·0	0·74	23 44 45·0
Frid.	**20**	S. 0 22·9	0·99	16 5	7 47·3	0·74	23 48 41·6
Sat.	**21**	N. 0 0·8	0·99	16 5	7 29·3	0·75	23 52 38·1
Sun.	**22**	N. 0 24·5	0·99	16 4	7 11·3	0·75	23 56 34·7
Mon.	**23**	0 48·2	0·99	16 4	6 53·2	0·76	0 0 31·2
Tues.	**24**	1 11·8	0·99	16 4	6 35·0	0·76	0 4 27·8
Wed.	**25**	N. 1 35·5	0·98	16 4	6 16·7	0·76	0 8 24·3
Thur.	**26**	1 59·1	0·98	16 3	5 58·5	0·76	0 12 20·9
Frid.	**27**	2 22·6	0·98	16 3	5 40·2	0·76	0 16 17·4
Sat.	**28**	N. 2 46·1	0·98	16 3	5 21·8	0·76	0 20 14·0
Sun.	**29**	3 9·6	0·98	16 2	5 3·5	0·76	0 24 10·5
Mon.	**30**	3 32·9	0·97	16 2	4 45·3	0·76	0 28 7·1
Tues.	**31**	3 56·2	0·97	16 2	4 27·1	0·76	0 32 3·7
Wed.	**32**	N. 4 19·5	0·97	16 2	4 8·9	0·75	0 36 0·2

Add for hours.

m s	h
0 9·9	1
0 19·7	2
0 29·6	3
0 39·4	4
0 49·3	5
0 59·1	6
1 9·0	7
1 18·9	8
1 28·7	9
1 38·6	10
1 48·4	11
1 58·3	12
2 8·1	13
2 18·0	14
2 27·8	15
2 37·7	16
2 47·6	17
2 57·4	18
3 7·3	19
3 17·1	20
3 27·0	21
3 36·8	22
3 46·7	23
3 56·6	24

Add for minutes.

s	m
0·2	1
0·3	2
0·5	3
0·7	4
0·8	5
1·0	6
1·1	7
1·3	8
1·5	9
1·6	10
3·3	20
4·9	30
6·6	40
8·2	50

MARCH, 1914.

MEAN TIME.

Date.		Transit of the First Point of Aries.	THE MOON.								
			Semi-diameter.	Var. in 1 hour.	Horizontal Parallax.	Var. in 1 hour.	Meridian Passage.				Age.
			Noon.		Noon.		Upper.	Diff.	Lower.	Diff.	Noon.
		h m s	′ ″	″	′ ″	″	h m	m	h m	m	d
Sun.	1	1 25 58·8	14 46	0·1	54 5	0·4	3 14	43	15 35	45	4·5
Mon.	2	1 22 2·9	14 49	0·2	54 18	0·7	3 57	47	16 20	48	5·5
Tues.	3	1 18 7·0	14 55	0·3	54 40	1·1	4 44	50	17 8	53	6·5
Wed.	4	1 14 11·1	15 4	0·4	55 12	1·5	5 34	54	18 1	55	7·5
Thur.	5	1 10 15·2	15 15	0·5	55 53	1·9	6 28	57	18 56	58	8·5
Frid.	6	1 6 19·3	15 29	0·6	56 42	2·2	7 25	57	19 54	57	9·5
Sat.	7	1 2 23·4	15 44	0·7	57 38	2·4	8 22	58	20 51	57	10·5
Sun.	8	0 58 27·5	16 0	0·7	58 36	2·4	9 20	55	21 48	54	11·5
Mon.	9	0 54 31·6	16 15	0·6	59 32	2·2	10 15	54	22 42	53	12·5
Tues.	10	0 50 35·7	16 28	0·5	60 21	1·8	11 9	51	23 35	51	13·5
Wed.	11	0 46 39·8	16 38	0·3	60 56	1·1	12 0	52	* *		14·5
Thur.	12	0 42 43·9	16 43	0·1	61 15	0·4	12 52	52	0 26	52	15·5
Frid.	13	0 38 47·9	16 43	0·1	61 13	0·5	13 44	54	1 18	52	16·5
Sat.	14	0 34 52·0	16 37	0·3	60 53	1·1	14 38	56	2 10	55	17·5
Sun.	15	0 30 56·1	16 27	0·5	60 18	1·7	15 34	59	3 5	58	18·5
Mon.	16	0 27 0·2	16 15	0·5	59 32	2·0	16 33	59	4 3	59	19·5
Tues.	17	0 23 4·3	16 1	0·6	58 41	2·1	17 32	60	5 2	60	20·5
Wed.	18	0 19 8·4	15 47	0·6	57 49	2·1	18 32	56	6 2	58	21·5
Thur.	19	0 15 12·5	15 33	0·5	57 0	2·0	19 28	52	7 0	55	22·5
Frid.	20	0 11 16·6	15 21	0·5	56 15	1·7	20 20	49	7 55	50	23·5
Sat.	21	0 7 20·7	15 11	0·4	55 37	1·4	21 9	44	8 45	46	24·5
Sun.	22	{0 3 24·8 23 59 28·9}	15 2	0·3	55 6	1·2	21 53	42	9 31	43	25·5
Mon.	23	23 55 33·0	14 56	0·2	54 41	0·9	22 35	39	10 14	41	26·5
Tues.	24	23 51 37·1	14 50	0·2	54 22	0·7	23 14	39	10 55	39	27·5
Wed.	25	23 47 41·1	14 47	0·1	54 8	0·5	23 53	39	11 34	39	28·5
Thur.	26	23 43 45·2	14 44	0·1	54 0	0·3	* *		12 13	39	29·5
Frid.	27	23 39 49·3	14 43	0·0	53 56	0·0	0 32	40	12 52	41	0·7
Sat.	28	23 35 53·4	14 44	0·1	53 58	0·2	1 12	43	13 33	44	1·7
Sun.	29	23 31 57·5	14 46	0·1	54 6	0·5	1 55	45	14 17	47	2·7
Mon.	30	23 28 1·6	14 50	0·2	54 20	0·7	2 40	49	15 4	50	3·7
Tues.	31	23 24 5·7	14 56	0·3	54 41	1·0	3 29	52	15 54	54	4·7
Wed.	32	23 20 9·8	15 4	0·4	55 10	1·4	4 21		16 48		5·7

MARCH, 1914.

THE SUN.

G.M.T.						
	Sunday 1			**Thursday 5**		
	R.A.M.S.	Dec.	Equation of Time.	R.A.M.S.	Dec.	Equation of Time.
h	h m s	° ′	m s	h m s	° ′	m s
0	22 33 47·0	S. 7 47·7	+12 38·5	22 49 33·3	S. 6 15·9	+11 48·6
2	22 34 6·7	7 45·8	12 37·5	22 49 53·0	6 14·0	11 47·5
4	22 34 26·4	7 43·9	12 36·6	22 50 12·7	6 12·0	11 46·3
6	22 34 46·1	7 42·0	12 35·6	22 50 32·4	6 10·1	11 45·2
8	22 35 5·9	7 40·1	12 34·6	22 50 52·2	6 8·2	11 44·1
10	22 35 25·6	7 38·2	12 33·7	22 51 11·9	6 6·2	11 42·9
12	22 35 45·3	7 36·3	12 32·7	22 51 31·6	6 4·3	11 41·8
14	22 36 5·0	7 34·4	12 31·7	22 51 51·3	6 2·4	11 40·7
16	22 36 24·7	7 32·5	12 30·8	22 52 11·0	6 0·4	11 39·5
18	22 36 44·5	7 30·6	12 29·8	22 52 30·7	5 58·5	11 38·4
20	22 37 4·2	7 28·7	12 28·8	22 52 50·4	5 56·6	11 37·2
22	22 37 23·9	7 26·8	12 27·8	22 53 10·1	5 54·6	11 36·1
	Monday 2			**Friday 6**		
0	22 37 43·6	S. 7 24·9	+12 26·8	22 53 29·8	S. 5 52·7	+11 34·9
2	22 38 3·3	7 23·0	12 25·8	22 53 49·5	5 50·8	11 33·7
4	22 38 23·0	7 21·1	12 24·8	22 54 9·2	5 48·8	11 32·6
6	22 38 42·7	7 19·2	12 23·8	22 54 28·9	5 46·9	11 31·4
8	22 39 2·5	7 17·3	12 22·8	22 54 48·7	5 45·0	11 30·2
10	22 39 22·2	7 15·4	12 21·7	22 55 8·4	5 43·0	11 29·1
12	22 39 41·9	7 13·5	12 20·7	22 55 28·1	5 41·1	11 27·9
14	22 40 1·6	7 11·6	12 19·7	22 55 47·8	5 39·2	11 26·7
16	22 40 21·3	7 9·7	12 18·6	22 56 7·5	5 37·2	11 25·6
18	22 40 41·0	7 7·8	12 17·6	22 56 27·3	5 35·3	11 24·4
20	22 41 0·7	7 5·9	12 16·6	22 56 47·0	5 33·4	11 23·2
22	22 41 20·4	7 3·9	12 15·5	22 57 6·7	5 31·4	11 22·0
	Tuesday 3			**Saturday 7**		
0	22 41 40·1	S. 7 2·0	+12 14·5	22 57 26·4	S. 5 29·5	+11 20·8
2	22 41 59·8	7 0·1	12 13·5	22 57 46·1	5 27·6	11 19·6
4	22 42 19·5	6 58·2	12 12·4	22 58 5·8	5 25·6	11 18·4
6	22 42 39·2	6 56·3	12 11·4	22 58 25·5	5 23·7	11 17·2
8	22 42 59·0	6 54·4	12 10·3	22 58 45·3	5 21·8	11 16·0
10	22 43 18·7	6 52·4	12 9·3	22 59 5·0	5 19·8	11 14·7
12	22 43 38·4	6 50·5	12 8·2	22 59 24·7	5 17·9	11 13·5
14	22 43 58·1	6 48·6	12 7·1	22 59 44·4	5 16·0	11 12·3
16	22 44 17·8	6 46·7	12 6·1	23 0 4·1	5 14·0	11 11·1
18	22 44 37·6	6 44·8	12 5·0	23 0 23·8	5 12·1	11 9·9
20	22 44 57·3	6 42·9	12 3·9	23 0 43·5	5 10·1	11 8·7
22	22 45 17·0	6 40·9	12 2·9	23 1 3·2	5 8·2	11 7·4
	Wednesday 4			**Sunday 8**		
0	22 45 36·7	S. 6 39·0	+12 1·8	23 1 22·9	S. 5 6·2	+11 6·2
2	22 45 56·4	6 37·1	12 0·7	23 1 42·6	5 4·3	11 5·0
4	22 46 16·1	6 35·2	11 59·7	23 2 2·3	5 2·3	11 3·7
6	22 46 35·8	6 33·3	11 58·6	23 2 22·0	5 0·4	11 2·5
8	22 46 55·6	6 31·4	11 57·5	23 2 41·8	4 58·4	11 1·3
10	22 47 15·3	6 29·4	11 56·4	23 3 1·5	4 56·5	11 0·0
12	22 47 35·0	6 27·5	11 55·3	23 3 21·2	4 54·5	10 58·8
14	22 47 54·7	6 25·6	11 54·2	23 3 40·9	4 52·6	10 57·6
16	22 48 14·4	6 23·6	11 53·1	23 4 0·6	4 50·6	10 56·3
18	22 48 34·2	6 21·7	11 52·0	23 4 20·4	4 48·7	10 55·1
20	22 48 53·9	6 19·8	11 50·9	23 4 40·1	4 46·7	10 53·8
22	22 49 13·6	S. 6 17·8	+11 49·7	23 4 59·8	S. 4 44·8	+10 52·6

The R.A. of Mer. (local Sidereal Time) is found by adding the Right Ascension of the Mean Sun to the local Mean Time.
The signs ± under Equation of Time denote *additive* or *subtractive* to Apparent Time and vice versâ to Mean Time.

MARCH, 1914.

G.M.T. THE SUN.

G.M.T.	R.A.M.S.	Dec.	Equation of Time.	R.A.M.S.	Dec.	Equation of Time.
	Monday 9			**Friday 13**		
h	h m s	° ′	m s	h m s	° ′	m s
0	23 5 19.5	S. 4 42.8	+10 51.3	23 21 5.7	S. 3 8.7	+ 9 48.0
2	23 5 39.2	4 40.9	10 50.0	23 21 25.4	3 6.7	9 46.6
4	23 5 58.9	4 38.9	10 48.8	23 21 45.1	3 4.8	9 45.3
6	23 6 18.6	4 37.0	10 47.5	23 22 4.8	3 2.8	9 43.9
8	23 6 38.4	4 35.0	10 46.2	23 22 24.6	3 0.8	9 42.5
10	23 6 58.1	4 33.1	10 45.0	23 22 44.3	2 58.9	9 41.1
12	23 7 17.8	4 31.1	10 43.7	23 23 4.0	2 56.9	9 39.7
14	23 7 37.5	4 29.1	10 42.4	23 23 23.7	2 54.9	9 38.3
16	23 7 57.2	4 27.2	10 41.2	23 23 43.4	2 53.0	9 37.0
18	23 8 16.9	4 25.2	10 39.9	23 24 3.1	2 51.0	9 35.6
20	23 8 36.6	4 23.2	10 38.6	23 24 22.8	2 49.0	9 34.2
22	23 8 56.3	4 21.3	10 37.3	23 24 42.5	2 47.1	9 32.8
	Tuesday 10			**Saturday 14**		
0	23 9 16.0	S. 4 19.3	+10 36.0	23 25 2.2	S. 2 45.1	+ 9 31.4
2	23 9 35.7	4 17.4	10 34.7	23 25 21.9	2 43.1	9 30.0
4	23 9 55.4	4 15.4	10 33.4	23 25 41.6	2 41.2	9 28.6
6	23 10 15.1	4 13.5	10 32.1	23 26 1.3	2 39.2	9 27.2
8	23 10 34.9	4 11.5	10 30.8	23 26 21.1	2 37.2	9 25.8
10	23 10 54.6	4 9.6	10 29.5	23 26 40.8	2 35.3	9 24.4
12	23 11 14.3	4 7.6	10 28.2	23 27 0.5	2 33.3	9 23.0
14	23 11 34.0	4 5.6	10 26.9	23 27 20.2	2 31.3	9 21.6
16	23 11 53.7	4 3.7	10 25.6	23 27 39.9	2 29.4	9 20.2
18	23 12 13.5	4 1.7	10 24.3	23 27 59.7	2 27.4	9 18.8
20	23 12 33.2	3 59.7	10 23.0	23 28 19.4	2 25.4	9 17.4
22	23 12 52.9	3 57.8	10 21.6	23 28 39.1	2 23.4	9 15.9
	Wednesday 11			**Sunday 15**		
0	23 13 12.6	S. 3 55.8	+10 20.3	23 28 58.8	S. 2 21.4	+ 9 14.5
2	23 13 32.3	3 53.9	10 19.0	23 29 18.5	2 19.4	9 13.1
4	23 13 52.0	3 51.9	10 17.6	23 29 38.2	2 17.5	9 11.7
6	23 14 11.7	3 50.0	10 16.3	23 29 57.9	2 15.5	9 10.3
8	23 14 31.5	3 48.0	10 15.0	23 30 17.7	2 13.5	9 8.9
10	23 14 51.2	3 46.1	10 13.6	23 30 37.4	2 11.6	9 7.4
12	23 15 10.9	3 44.1	10 12.3	23 30 57.1	2 9.6	9 6.0
14	23 15 30.6	3 42.1	10 11.0	23 31 16.8	2 7.6	9 4.6
16	23 15 50.3	3 40.2	10 9.6	23 31 36.5	2 5.7	9 3.2
18	23 16 10.0	3 38.2	10 8.3	23 31 56.3	2 3.7	9 1.8
20	23 16 29.7	3 36.2	10 7.0	23 32 16.0	2 1.7	9 0.4
22	23 16 49.4	3 34.3	10 5.6	23 32 35.7	1 59.8	8 58.9
	Thursday 12			**Monday 16**		
0	23 17 9.1	S. 3 32.3	+10 4.3	23 32 55.4	S. 1 57.8	+ 8 57.5
2	23 17 28.8	3 30.3	10 3.0	23 33 15.1	1 55.8	8 56.1
4	23 17 48.5	3 28.4	10 1.6	23 33 34.8	1 53.9	8 54.6
6	23 18 8.2	3 26.4	10 0.3	23 33 54.5	1 51.9	8 53.2
8	23 18 28.0	3 24.4	9 58.9	23 34 14.3	1 49.9	8 51.8
10	23 18 47.7	3 22.5	9 57.6	23 34 34.0	1 48.0	8 50.3
12	23 19 7.4	3 20.5	9 56.2	23 34 53.7	1 46.0	8 48.9
14	23 19 27.1	3 18.5	9 54.8	23 35 13.4	1 44.0	8 47.5
16	23 19 46.8	3 16.6	9 53.5	23 35 33.1	1 42.1	8 46.0
18	23 20 6.6	3 14.6	9 52.1	23 35 52.8	1 40.1	8 44.6
20	23 20 26.3	3 12.6	9 50.7	23 36 12.5	1 38.1	8 43.1
22	23 20 46.0	S. 3 10.7	+ 9 49.4	23 36 32.2	S. 1 36.1	+ 8 41.7

The R.A. of Mer. (local Sidereal Time) is found by adding the Right Ascension of the Mean Sun to the local Mean Time.
The signs ± under Equation of Time denote *additive* or *subtractive* to Apparent Time and vice versâ to Mean Time.

MARCH, 1914.

THE SUN.

G.M.T. h	R.A.M.S. h m s	Dec. ° ′	Equation of Time. m s	R.A.M.S. h m s	Dec. ° ′	Equation of Time. m s
	Tuesday 17			**Saturday 21**		
0	23 36 51·9	S. 1 34·1	+ 8 40·2	23 52 38·1	N. 0 0·8	+ 7 29·3
2	23 37 11·6	1 32·1	8 38·8	23 52 57·8	0 2·8	7 27·8
4	23 37 31·3	1 30·2	8 37·3	23 53 17·5	0 4·8	7 26·3
6	23 37 51·0	1 28·2	8 35·9	23 53 37·2	0 6·8	7 24·8
8	23 38 10·8	1 26·2	8 34·4	23 53 57·0	0 8·8	7 23·3
10	23 38 30·5	1 24·2	8 33·0	23 54 16·7	0 10·7	7 21·8
12	23 38 50·2	1 22·2	8 31·5	23 54 36·4	0 12·7	7 20·3
14	23 39 9·9	1 20·2	8 30·0	23 54 56·1	0 14·7	7 18·8
16	23 39 29·6	1 18·3	8 28·6	23 55 15·8	0 16·6	7 17·3
18	23 39 49·4	1 16·3	8 27·1	23 55 35·6	0 18·6	7 15·8
20	23 40 9·1	1 14·3	8 25·6	23 55 55·3	0 20·6	7 14·3
22	23 40 28·8	1 12·3	8 24·2	23 56 15·0	0 22·5	7 12·8
	Wednesday 18			**Sunday 22**		
0	23 40 48·5	S. 1 10·3	+ 8 22·7	23 56 34·7	N. 0 24·5	+ 7 11·3
2	23 41 8·2	1 8·3	8 21·2	23 56 54·4	0 26·5	7 9·8
4	23 41 27·9	1 6·4	8 19·8	23 57 14·1	0 28·5	7 8·3
6	23 41 47·6	1 4·4	8 18·3	23 57 33·8	0 30·5	7 6·8
8	23 42 7·4	1 2·4	8 16·8	23 57 53·6	0 32·5	7 5·3
10	23 42 27·1	1 0·5	8 15·4	23 58 13·3	0 34·4	7 3·8
12	23 42 46·8	0 58·5	8 13·9	23 58 33·0	0 36·4	7 2·3
14	23 43 6·5	0 56·5	8 12·4	23 58 52·7	0 38·4	7 0·8
16	23 43 26·2	0 54·6	8 11·0	23 59 12·4	0 40·3	6 59·3
18	23 43 45·9	0 52·6	8 9·5	23 59 32·1	0 42·3	6 57·8
20	23 44 5·6	0 50·6	8 8·0	23 59 51·8	0 44·3	6 56·3
22	23 44 25·3	0 48·6	8 6·5	0 0 11·5	0 46·2	6 54·7
	Thursday 19			**Monday 23**		
0	23 44 45·0	S. 0 46·6	+ 8 5·0	0 0 31·2	N. 0 48·2	+ 6 53·2
2	23 45 4·7	0 44·6	8 3·5	0 0 50·9	0 50·2	6 51·7
4	23 45 24·4	0 42·7	8 2·1	0 1 10·6	0 52·1	6 50·2
6	23 45 44·1	0 40·7	8 0·6	0 1 30·3	0 54·1	6 48·7
8	23 46 3·9	0 38·7	7 59·1	0 1 50·1	0 56·1	6 47·2
10	23 46 23·6	0 36·8	7 57·7	0 2 9·8	0 58·0	6 45·6
12	23 46 43·3	0 34·8	7 56·2	0 2 29·5	1 0·0	6 44·1
14	23 47 3·0	0 32·8	7 54·7	0 2 49·2	1 2·0	6 42·6
16	23 47 22·7	0 30·9	7 53·3	0 3 8·9	1 3·9	6 41·1
18	23 47 42·5	0 28·9	7 51·8	0 3 28·7	1 5·9	6 39·6
20	23 48 2·2	0 26·9	7 50·3	0 3 48·4	1 7·9	6 38·1
22	23 48 21·9	0 24·9	7 48·8	0 4 8·1	1 9·8	6 36·5
	Friday 20			**Tuesday 24**		
0	23 48 41·6	S. 0 22·9	+ 7 47·3	0 4 27·8	N. 1 11·8	+ 6 35·0
2	23 49 1·3	0 20·9	7 45·8	0 4 47·5	1 13·8	6 33·5
4	23 49 21·0	0 19·0	7 44·3	0 5 7·2	1 15·8	6 32·0
6	23 49 40·7	0 17·0	7 42·8	0 5 26·9	1 17·8	6 30·5
8	23 50 0·5	0 15·0	7 41·3	0 5 46·7	1 19·8	6 29·0
10	23 50 20·2	0 13·1	7 39·8	0 6 6·4	1 21·7	6 27·4
12	23 50 39·9	0 11·1	7 38·3	0 6 26·1	1 23·7	6 25·9
14	23 50 59·6	0 9·1	7 36·8	0 6 45·8	1 25·7	6 24·4
16	23 51 19·3	0 7·2	7 35·3	0 7 5·5	1 27·6	6 22·8
18	23 51 39·0	0 5·2	7 33·8	0 7 25·2	1 29·6	6 21·3
20	23 51 58·7	0 3·2	7 32·3	0 7 44·9	1 31·6	6 19·8
22	23 52 18·4	S. 0 1·2	+ 7 30·8	0 8 4·6	N. 1 33·5	+ 6 18·2

The R.A. of Mer. (local Sidereal Time) is found by adding the Right Ascension of the Mean Sun to the local Mean Time.
The signs ± under Equation of Time denote *additive* or *subtractive* to Apparent Time and vice versâ to Mean Time.

MARCH, 1914.

THE SUN.

G.M.T.

Wednesday 25

h	R.A.M.S. h m s	Dec. ° ′	Equation of Time m s
0	0 8 24·3	N. 1 35·5	+ 6 16·7
2	0 8 44·0	1 37·5	6 15·2
4	0 9 3·7	1 39·4	6 13·7
6	0 9 23·4	1 41·4	6 12·2
8	0 9 43·2	1 43·4	6 10·7
10	0 10 2·9	1 45·3	6 9·1
12	0 10 22·6	1 47·3	6 7·6
14	0 10 42·3	1 49·3	6 6·1
16	0 11 2·0	1 51·2	6 4·6
18	0 11 21·8	1 53·2	6 3·1
20	0 11 41·5	1 55·2	6 1·6
22	0 12 1·2	1 57·1	6 0·0

Thursday 26

h	R.A.M.S. h m s	Dec. ° ′	Equation of Time m s
0	0 12 20·9	N. 1 59·1	+ 5 58·5
2	0 12 40·6	2 1·1	5 57·0
4	0 13 0·3	2 3·0	5 55·5
6	0 13 20·0	2 5·0	5 54·0
8	0 13 39·8	2 7·0	5 52·5
10	0 13 59·5	2 8·9	5 50·9
12	0 14 19·2	2 10·9	5 49·4
14	0 14 38·9	2 12·9	5 47·9
16	0 14 58·6	2 14·8	5 46·3
18	0 15 18·3	2 16·8	5 44·8
20	0 15 38·0	2 18·7	5 43·3
22	0 15 57·7	2 20·7	5 41·7

Friday 27

h	R.A.M.S. h m s	Dec. ° ′	Equation of Time m s
0	0 16 17·4	N. 2 22·6	+ 5 40·2
2	0 16 37·1	2 24·6	5 38·7
4	0 16 56·8	2 26·5	5 37·1
6	0 17 16·5	2 28·5	5 35·6
8	0 17 36·3	2 30·5	5 34·1
10	0 17 56·0	2 32·4	5 32·5
12	0 18 15·7	2 34·4	5 31·0
14	0 18 35·4	2 36·4	5 29·5
16	0 18 55·1	2 38·3	5 27·9
18	0 19 14·9	2 40·3	5 26·4
20	0 19 34·6	2 42·2	5 24·9
22	0 19 54·3	2 44·2	5 23·3

Saturday 28

h	R.A.M.S. h m s	Dec. ° ′	Equation of Time m s
0	0 20 14·0	N. 2 46·1	+ 5 21·8
2	0 20 33·7	2 48·1	5 20·3
4	0 20 53·4	2 50·0	5 18·8
6	0 21 13·1	2 52·0	5 17·3
8	0 21 32·9	2 54·0	5 15·8
10	0 21 52·6	2 55·9	5 14·2
12	0 22 12·3	2 57·9	5 12·7
14	0 22 32·0	2 59·9	5 11·2
16	0 22 51·7	3 1·8	5 9·6
18	0 23 11·4	3 3·8	5 8·1
20	0 23 31·1	3 5·7	5 6·6
22	0 23 50·8	N. 3 7·7	+ 5 5·0

Sunday 29

h	R.A.M.S. h m s	Dec. ° ′	Equation of Time m s
0	0 24 10·5	N. 3 9·6	+ 5 3·5
2	0 24 30·2	3 11·6	5 2·0
4	0 24 49·9	3 13·5	5 0·5
6	0 25 9·6	3 15·5	4 59·0
8	0 25 29·4	3 17·4	4 57·5
10	0 25 49·1	3 19·4	4 55·9
12	0 26 8·8	3 21·3	4 54·4
14	0 26 28·5	3 23·2	4 52·9
16	0 26 48·2	3 25·2	4 51·4
18	0 27 8·0	3 27·1	4 49·9
20	0 27 27·7	3 29·0	4 48·4
22	0 27 47·4	3 31·0	4 46·8

Monday 30

h	R.A.M.S. h m s	Dec. ° ′	Equation of Time m s
0	0 28 7·1	N. 3 32·9	+ 4 45·3
2	0 28 26·8	3 34·9	4 43·8
4	0 28 46·5	3 36·8	4 42·3
6	0 29 6·2	3 38·8	4 40·8
8	0 29 26·0	3 40·7	4 39·3
10	0 29 45·7	3 42·7	4 37·7
12	0 30 5·4	3 44·6	4 36·2
14	0 30 25·1	3 46·5	4 34·7
16	0 30 44·8	3 48·5	4 33·2
18	0 31 4·6	3 50·4	4 31·7
20	0 31 24·3	3 52·3	4 30·2
22	0 31 44·0	3 54·3	4 28·6

Tuesday 31

h	R.A.M.S. h m s	Dec. ° ′	Equation of Time m s
0	0 32 3·7	N. 3 56·2	+ 4 27·1
2	0 32 23·4	3 58·2	4 25·6
4	0 32 43·1	4 0·1	4 24·1
6	0 33 2·8	4 2·1	4 22·6
8	0 33 22·6	4 4·0	4 21·1
10	0 33 42·3	4 6·0	4 19·5
12	0 34 2·0	4 7·9	4 18·0
14	0 34 21·7	4 9·8	4 16·5
16	0 34 41·4	4 11·8	4 15·0
18	0 35 1·1	4 13·7	4 13·5
20	0 35 20·8	4 15·6	4 12·0
22	0 35 40·5	4 17·6	4 10·4
24	0 36 0·2	N. 4 19·5	+ 4 8·9

The R.A. of Mer. (local Sidereal Time) is found by adding the Right Ascension of the Mean Sun to the local Mean Time. The signs ± under Equation of Time denote *additive* or *subtractive* to Apparent Time and vice versâ to Mean Time.

MARCH, 1914.

MOON'S RIGHT ASCENSION AND DECLINATION.

G.M.T.	R.A.				Dec.		
h	h	m	s		°	′	
Sunday 1							
0	1	42	14	222	N. 14	33·1	248
2	1	45	56	223	14	57·9	245
4	1	49	39	224	15	22·4	244
6	1	53	23	224	15	46·8	241
8	1	57	7	226	16	10·9	238
10	2	0	53	227	16	34·7	237
12	2	4	40	228	16	58·4	233
14	2	8	28	229	17	21·7	232
16	2	12	17	230	17	44·9	228
18	2	16	7	232	18	7·7	226
20	2	19	59	232	18	30·3	223
22	2	23	51	234	N. 18	52·6	220
Monday 2							
0	2	27	45	235	N. 19	14·6	217
2	2	31	40	236	19	36·3	214
4	2	35	36	237	19	57·7	211
6	2	39	33	239	20	18·8	208
8	2	43	32	240	20	39·6	204
10	2	47	32	241	21	0·0	202
12	2	51	33	243	21	20·2	198
14	2	55	36	244	21	40·0	194
16	2	59	40	245	21	59·4	191
18	3	3	45	247	22	18·5	187
20	3	7	52	248	22	37·2	183
22	3	12	0	249	N. 22	55·5	180
Tuesday 3							
0	3	16	9	251	N. 23	13·5	176
2	3	20	20	253	23	31·1	171
4	3	24	33	254	23	48·2	168
6	3	28	47	255	24	5·0	163
8	3	33	2	257	24	21·3	160
10	3	37	19	258	24	37·3	155
12	3	41	37	260	24	52·8	150
14	3	45	57	261	25	7·8	146
16	3	50	18	262	25	22·4	141
18	3	54	40	264	25	36·5	137
20	3	59	4	266	25	50·2	132
22	4	3	30	267	N. 26	3·4	127
Wednesday 4							
0	4	7	57	268	N. 26	16·1	122
2	4	12	25	270	26	28·3	117
4	4	16	55	271	26	40·0	112
6	4	21	26	273	26	51·2	107
8	4	25	59	274	27	1·9	102
10	4	30	33	275	27	12·1	96
12	4	35	8	277	27	21·7	90
14	4	39	45	278	27	30·7	85
16	4	44	23	279	27	39·2	80
18	4	49	2	281	27	47·2	74
20	4	53	43	281	27	54·6	67
22	4	58	24	283	28	1·3	63
24	5	3	7		N. 28	7·6	

G.M.T.	R.A.				Dec.		
h	h	m	s		°	′	
Thursday 5							
0	5	3	7	284	N. 28	7·6	56
2	5	7	51	286	28	13·2	50
4	5	12	37	286	28	18·2	44
6	5	17	23	288	28	22·6	38
8	5	22	11	288	28	26·4	31
10	5	26	59	289	28	29·5	26
12	5	31	48	291	28	32·1	19
14	5	36	39	291	28	34·0	12
16	5	41	30	292	28	35·2	6
18	5	46	22	293	28	35·8	0
20	5	51	15	293	28	35·8	7
22	5	56	8	295	N. 28	35·1	14
Friday 6							
0	6	1	3	295	N. 28	33·7	20
2	6	5	58	295	28	31·7	27
4	6	10	53	296	28	29·0	34
6	6	15	49	296	28	25·6	40
8	6	20	45	297	28	21·6	48
10	6	25	42	297	28	16·8	54
12	6	30	39	298	28	11·4	61
14	6	35	37	298	28	5·3	68
16	6	40	35	298	27	58·5	74
18	6	45	33	298	27	51·1	82
20	6	50	31	298	27	42·9	89
22	6	55	29	298	N. 27	34·0	95
Saturday 7							
0	7	0	27	298	N. 27	24·5	103
2	7	5	25	298	27	14·2	109
4	7	10	23	298	27	3·3	116
6	7	15	21	298	26	51·7	123
8	7	20	19	298	26	39·4	130
10	7	25	17	297	26	26·4	136
12	7	30	14	297	26	12·8	144
14	7	35	11	297	25	58·4	150
16	7	40	8	296	25	43·4	157
18	7	45	4	296	25	27·7	163
20	7	50	0	295	25	11·4	170
22	7	54	55	295	N. 24	54·4	177
Sunday 8							
0	7	59	50	294	N. 24	36·7	183
2	8	4	44	293	24	18·4	189
4	8	9	37	293	23	59·5	196
6	8	14	30	293	23	39·9	203
8	8	19	23	291	23	19·6	208
10	8	24	14	291	22	58·8	215
12	8	29	5	291	22	37·3	220
14	8	33	56	289	22	15·3	227
16	8	38	45	289	21	52·6	232
18	8	43	34	288	21	29·4	239
20	8	48	22	287	21	5·5	243
22	8	53	9	287	20	41·2	250
24	8	57	56		N. 20	16·2	

MARCH, 1914.

MOON'S RIGHT ASCENSION AND DECLINATION.

G.M.T. h	R.A. h	m	s		Dec. °	′	
	Monday 9						
0	8	57	56	285	N. 20	16·2	255
2	9	2	41	285	19	50·7	261
4	9	7	26	284	19	24·6	265
6	9	12	10	283	18	58·1	271
8	9	16	53	283	18	31·0	276
10	9	21	36	281	18	3·4	281
12	9	26	17	281	17	35·3	286
14	9	30	58	280	17	6·7	290
16	9	35	38	279	16	37·7	295
18	9	40	17	279	16	8·2	300
20	9	44	56	278	15	38·2	304
22	9	49	34	277	N. 15	7·8	307
	Tuesday 10						
0	9	54	11	276	N. 14	37·1	312
2	9	58	47	275	14	5·9	316
4	10	3	22	275	13	34·3	320
6	10	7	57	275	13	2·3	323
8	10	12	32	273	12	30·0	327
10	10	17	5	273	11	57·3	330
12	10	21	38	272	11	24·3	333
14	10	26	10	272	10	51·0	337
16	10	30	42	271	10	17·3	339
18	10	35	13	271	9	43·4	342
20	10	39	44	270	9	9·2	344
22	10	44	14	270	N. 8	34·8	347
	Wednesday 11						
0	10	48	44	270	N. 8	0·1	349
2	10	53	14	269	7	25·2	352
4	10	57	43	268	6	50·0	353
6	11	2	11	269	6	14·7	355
8	11	6	40	268	5	39·2	357
10	11	11	8	267	5	3·5	358
12	11	15	35	268	4	27·7	359
14	11	20	3	267	3	51·8	361
16	11	24	30	268	3	15·7	362
18	11	28	58	267	2	39·5	362
20	11	33	25	267	2	3·3	363
22	11	37	52	267	N. 1	27·0	364
	Thursday 12						
0	11	42	19	267	N. 0	50·6	364
2	11	46	46	267	N. 0	14·2	364
4	11	51	13	268	S. 0	22·2	364
6	11	55	41	267	0	58·6	364
8	12	0	8	268	1	35·0	363
10	12	4	36	267	2	11·3	363
12	12	9	3	268	2	47·6	363
14	12	13	31	269	3	23·9	361
16	12	18	0	268	4	0·0	360
18	12	22	28	269	4	36·0	360
20	12	26	57	270	5	12·0	358
22	12	31	27	269	5	47·8	356
24	12	35	56		S. 6	23·4	

G.M.T. h	R.A. h	m	s		Dec. °	′	
	Friday 13						
0	12	35	56	271	S. 6	23·4	355
2	12	40	27	270	6	58·9	353
4	12	44	57	272	7	34·2	351
6	12	49	29	272	8	9·3	348
8	12	54	1	272	8	44·1	347
10	12	58	33	273	9	18·8	344
12	13	3	6	274	9	53·2	341
14	13	7	40	274	10	27·3	338
16	13	12	14	276	11	1·1	336
18	13	16	50	276	11	34·7	332
20	13	21	26	276	12	7·9	329
22	13	26	2	278	S. 12	40·8	326
	Saturday 14						
0	13	30	40	278	S. 13	13·4	322
2	13	35	18	279	13	45·6	318
4	13	39	57	281	14	17·4	314
6	13	44	38	281	14	48·8	311
8	13	49	19	282	15	19·9	306
10	13	54	1	282	15	50·5	302
12	13	58	43	284	16	20·7	297
14	14	3	27	285	16	50·4	293
16	14	8	12	286	17	19·7	288
18	14	12	58	286	17	48·5	283
20	14	17	44	288	18	16·8	278
22	14	22	32	289	S. 18	44·6	273
	Sunday 15						
0	14	27	21	289	S. 19	11·9	267
2	14	32	10	291	19	38·6	263
4	14	37	1	292	20	4·9	256
6	14	41	53	292	20	30·5	251
8	14	46	45	294	20	55·6	246
10	14	51	39	294	21	20·2	239
12	14	56	33	296	21	44·1	234
14	15	1	29	296	22	7·5	227
16	15	6	25	298	22	30·2	221
18	15	11	23	298	22	52·3	215
20	15	16	21	299	23	13·8	208
22	15	21	20	300	S. 23	34·6	202
	Monday 16						
0	15	26	20	300	S. 23	54·8	196
2	15	31	20	302	24	14·4	189
4	15	36	22	302	24	33·3	182
6	15	41	24	303	24	51·5	175
8	15	46	27	304	25	9·0	168
10	15	51	31	304	25	25·8	162
12	15	56	35	305	25	42·0	154
14	16	1	40	305	25	57·4	148
16	16	6	45	306	26	12·2	140
18	16	11	51	306	26	26·2	133
20	16	16	57	307	26	39·5	126
22	16	22	4	307	26	52·1	119
24	16	27	11		S. 27	4·0	

MOON'S RIGHT ASCENSION AND DECLINATION.

Tuesday 17

G.M.T. h	R.A. h	m	s		Dec. °	′	
0	16	27	11	307	S. 27	4·0	112
2	16	32	18	307	27	15·2	104
4	16	37	25	308	27	25·6	97
6	16	42	33	308	27	35·3	90
8	16	47	41	307	27	44·3	82
10	16	52	48	308	27	52·5	75
12	16	57	56	307	28	0·0	68
14	17	3	3	308	28	6·8	61
16	17	8	11	307	28	12·9	53
18	17	13	18	307	28	18·2	46
20	17	18	25	306	28	22·8	39
22	17	23	31	306	S. 28	26·7	31

Wednesday 18

G.M.T. h	R.A. h	m	s		Dec. °	′	
0	17	28	37	306	S. 28	29·8	24
2	17	33	43	305	28	32·2	17
4	17	38	48	304	28	33·9	10
6	17	43	52	304	28	34·9	3
8	17	48	56	303	28	35·2	4
10	17	53	59	302	28	34·8	11
12	17	59	1	302	28	33·7	18
14	18	4	3	300	28	31·9	25
16	18	9	3	300	28	29·4	32
18	18	14	3	298	28	26·2	38
20	18	19	1	298	28	22·4	45
22	18	23	59	296	28	17·9	52

Thursday 19

G.M.T. h	R.A. h	m	s		Dec. °	′	
0	18	28	55	295	S. 28	12·7	58
2	18	33	50	294	28	6·9	65
4	18	38	44	292	28	0·4	71
6	18	43	36	292	27	53·3	77
8	18	48	28	290	27	45·6	83
10	18	53	18	288	27	37·3	89
12	18	58	6	288	27	28·4	96
14	19	2	54	285	27	18·8	101
16	19	7	39	285	27	8·7	107
18	19	12	24	283	26	58·0	113
20	19	17	7	281	26	46·7	118
22	19	21	48	280	S. 26	34·9	124

Friday 20

G.M.T. h	R.A. h	m	s		Dec. °	′	
0	19	26	28	278	S. 26	22·5	129
2	19	31	6	277	26	9·6	134
4	19	35	43	275	25	56·2	140
6	19	40	18	273	25	42·2	145
8	19	44	51	272	25	27·7	149
10	19	49	23	270	25	12·8	155
12	19	53	53	269	24	57·3	159
14	19	58	22	267	24	41·4	164
16	20	2	49	265	24	25·0	169
18	20	7	14	264	24	8·1	173
20	20	11	38	262	23	50·8	177
22	20	16	0	261	23	33·1	182
24	20	20	21		S. 23	14·9	

Saturday 21

G.M.T. h	R.A. h	m	s		Dec. °	′	
0	20	20	21	259	S. 23	14·9	186
2	20	24	40	257	22	56·3	190
4	20	28	57	256	22	37·3	193
6	20	33	13	254	22	18·0	198
8	20	37	27	253	21	58·2	202
10	20	41	40	251	21	38·0	205
12	20	45	51	249	21	17·5	208
14	20	50	0	248	20	56·7	212
16	20	54	8	247	20	35·5	216
18	20	58	15	245	20	13·9	219
20	21	2	20	244	19	52·0	222
22	21	6	24	242	S. 19	29·8	225

Sunday 22

G.M.T. h	R.A. h	m	s		Dec. °	′	
0	21	10	26	241	S. 19	7·3	228
2	21	14	27	239	18	44·5	231
4	21	18	26	238	18	21·4	233
6	21	22	24	237	17	58·1	237
8	21	26	21	236	17	34·4	239
10	21	30	17	234	17	10·5	242
12	21	34	11	233	16	46·3	244
14	21	38	4	231	16	21·9	246
16	21	41	55	231	15	57·3	249
18	21	45	46	229	15	32·4	251
20	21	49	35	229	15	7·3	253
22	21	53	24	227	S. 14	42·0	255

Monday 23

G.M.T. h	R.A. h	m	s		Dec. °	′	
0	21	57	11	226	S. 14	16·5	258
2	22	0	57	225	13	50·7	259
4	22	4	42	224	13	24·8	261
6	22	8	26	223	12	58·7	263
8	22	12	9	222	12	32·4	264
10	22	15	51	221	12	6·0	266
12	22	19	32	220	11	39·4	267
14	22	23	12	219	11	12·7	269
16	22	26	51	219	10	45·8	271
18	22	30	30	218	10	18·7	271
20	22	34	8	217	9	51·6	273
22	22	37	45	216	9	24·3	274

Tuesday 24

G.M.T. h	R.A. h	m	s		Dec. °	′	
0	22	41	21	216	S. 8	56·9	276
2	22	44	57	215	8	29·3	276
4	22	48	32	214	8	1·7	277
6	22	52	6	214	7	34·0	278
8	22	55	40	213	7	6·2	279
10	22	59	13	212	6	38·3	280
12	23	2	45	213	6	10·3	280
14	23	6	18	211	5	42·3	281
16	23	9	49	211	5	14·2	282
18	23	13	20	211	4	46·0	282
20	23	16	51	211	4	17·8	283
22	23	20	22	210	3	49·5	283
24	23	23	52		S. 3	21·2	

MARCH, 1914.

MOON'S RIGHT ASCENSION AND DECLINATION.

Wednesday 25

G.M.T. h	R.A. h	m	s		Dec. °	′	
0	23	23	52	210	S. 3	21·2	283
2	23	27	22	209	2	52·9	283
4	23	30	51	209	2	24·6	284
6	23	34	20	209	1	56·2	284
8	23	37	49	209	1	27·8	284
10	23	41	18	209	0	59·4	284
12	23	44	47	209	0	31·0	284
14	23	48	16	208	S. 0	2·6	284
16	23	51	44	209	N. 0	25·8	284
18	23	55	13	208	0	54·2	283
20	23	58	41	209	1	22·5	283
22	0	2	10	209	N. 1	50·8	283

Thursday 26

G.M.T. h	R.A. h	m	s		Dec. °	′	
0	0	5	39	208	N. 2	19·1	282
2	0	9	7	209	2	47·3	282
4	0	12	36	209	3	15·5	282
6	0	16	5	209	3	43·7	281
8	0	19	34	209	4	11·8	280
10	0	23	3	210	4	39·8	279
12	0	26	33	210	5	7·7	279
14	0	30	3	210	5	35·6	278
16	0	33	33	210	6	3·4	277
18	0	37	3	211	6	31·1	276
20	0	40	34	211	6	58·7	275
22	0	44	5	212	N. 7	26·2	274

Friday 27

G.M.T. h	R.A. h	m	s		Dec. °	′	
0	0	47	37	212	N. 7	53·6	273
2	0	51	9	212	8	20·9	271
4	0	54	41	213	8	48·0	270
6	0	58	14	214	9	15·0	269
8	1	1	48	214	9	41·9	268
10	1	5	22	215	10	8·7	266
12	1	8	57	215	10	35·3	265
14	1	12	32	216	11	1·8	263
16	1	16	8	217	11	28·1	261
18	1	19	45	217	11	54·2	260
20	1	23	22	218	12	20·2	258
22	1	27	0	219	N. 12	46·0	256

Saturday 28

G.M.T. h	R.A. h	m	s		Dec. °	′	
0	1	30	39	220	N. 13	11·6	254
2	1	34	19	220	13	37·0	252
4	1	37	59	222	14	2·2	250
6	1	41	41	222	14	27·2	248
8	1	45	23	223	14	52·0	246
10	1	49	6	224	15	16·6	243
12	1	52	50	225	15	40·9	242
14	1	56	35	226	16	5·1	238
16	2	0	21	227	16	28·9	237
18	2	4	8	228	16	52·6	233
20	2	7	56	229	17	15·9	232
22	2	11	45	230	17	39·1	228
24	2	15	35		N. 18	1·9	

Sunday 29

G.M.T. h	R.A. h	m	s		Dec. °	′	
0	2	15	35	232	N. 18	1·9	226
2	2	19	27	232	18	24·5	223
4	2	23	19	233	18	46·8	220
6	2	27	12	235	19	8·8	217
8	2	31	7	236	19	30·5	213
10	2	35	3	236	19	51·8	211
12	2	38	59	239	20	12·9	208
14	2	42	58	239	20	33·7	204
16	2	46	57	240	20	54·1	201
18	2	50	57	242	21	14·2	197
20	2	54	59	243	21	33·9	194
22	2	59	2	244	N. 21	53·3	191

Monday 30

G.M.T. h	R.A. h	m	s		Dec. °	′	
0	3	3	6	246	N. 22	12·4	186
2	3	7	12	247	22	31·0	183
4	3	11	19	248	22	49·3	179
6	3	15	27	249	23	7·2	175
8	3	19	36	251	23	24·7	171
10	3	23	47	252	23	41·8	167
12	3	27	59	254	23	58·5	163
14	3	32	13	254	24	14·8	159
16	3	36	27	256	24	30·7	154
18	3	40	43	258	24	46·1	150
20	3	45	1	258	25	1·1	145
22	3	49	19	260	N. 25	15·6	141

Tuesday 31

G.M.T. h	R.A. h	m	s		Dec. °	′	
0	3	53	39	261	N. 25	29·7	136
2	3	58	0	263	25	43·3	132
4	4	2	23	263	25	56·5	126
6	4	6	46	265	26	9·1	122
8	4	11	11	266	26	21·3	117
10	4	15	37	268	26	33·0	111
12	4	20	5	269	26	44·1	107
14	4	24	34	269	26	54·8	102
16	4	29	3	271	27	5·0	96
18	4	33	34	273	27	14·6	91
20	4	38	7	273	27	23·7	85
22	4	42	40	274	27	32·2	80
24	4	47	14		N. 27	40·2	

PHASES OF THE MOON.

			h	m
Mar. 4	☽	*First Quarter* - -	17	3
11	○	Full Moon - - -	16	19
18	☾	*Last Quarter* - -	7	39
26	●	New Moon - - -	6	9

			h
Mar. 12	☾	Perigee - - - - - -	10·3
27	☾	Apogee - - - - - -	3·5

MARCH, 1914.

MEAN TIME.

		VENUS.					MARS.				
		At Greenwich Mean Noon.				Meridian Passage.	At Greenwich Mean Noon.				Meridian Passage.
		R.A.		Dec.			R.A.		Dec.		
		h m s		° ′		h m	h m s		° ′		h m
Sun.	**1**	23 4 42	278	S. 7 28·6	292	0 31	6 32 18	50	N.26 26·8	21	7 58
Mon.	**2**	23 9 20	278	6 59·4	294	0 32	6 33 8	51	26 24·7	22	7 54
Tues.	**3**	23 13 58	277	6 30·0	296	0 32	6 33 59	55	26 22·5	22	7 51
Wed.	**4**	23 18 35	276	6 0·4	297	0 33	6 34 54	56	26 20·3	23	7 48
Thur.	**5**	23 23 11	276	5 30·7	299	0 34	6 35 50	59	26 18·0	23	7 45
Frid.	**6**	23 27 47	275	5 0·8	300	0 34	6 36 49	61	26 15·7	24	7 42
Sat.	**7**	23 32 22	275	4 30·8	301	0 35	6 37 50	63	26 13·3	24	7 40
Sun.	**8**	23 36 57	274	4 0·7	303	0 36	6 38 53	65	26 10·9	24	7 37
Mon.	**9**	23 41 31	274	3 30·4	303	0 36	6 39 58	67	26 8·5	26	7 34
Tues.	**10**	23 46 5	273	3 0·1	304	0 37	6 41 5	69	26 5·9	25	7 31
Wed.	**11**	23 50 38	273	2 29·7	305	0 38	6 42 14	71	26 3·4	26	7 28
Thur.	**12**	23 55 11	273	1 59·2	306	0 38	6 43 25	73	26 0·8	27	7 25
Frid.	**13**	23 59 44	273	1 28·6	306	0 39	6 44 38	75	25 58·1	28	7 23
Sat.	**14**	0 4 17	272	0 58·0	306	0 39	6 45 53	77	25 55·3	28	7 20
Sun.	**15**	0 8 49	272	S. 0 27·4	307	0 40	6 47 10	78	25 52·5	28	7 17
Mon.	**16**	0 13 21	273	N. 0 3·3	306	0 41	6 48 28	80	25 49·7	29	7 15
Tues.	**17**	0 17 54	272	0 33·9	307	0 41	6 49 48	82	25 46·8	30	7 12
Wed.	**18**	0 22 26	272	1 4·6	307	0 42	6 51 10	83	25 43·8	31	7 10
Thur.	**19**	0 26 58	272	1 35·3	306	0 42	6 52 33	85	25 40·7	31	7 7
Frid.	**20**	0 31 30	272	2 5·9	306	0 43	6 53 58	86	25 37·6	32	7 5
Sat.	**21**	0 36 2	273	2 36·5	306	0 43	6 55 24	88	25 34·4	33	7 2
Sun.	**22**	0 40 35	272	3 7·1	305	0 44	6 56 52	89	25 31·1	33	7 0
Mon.	**23**	0 45 7	273	3 37·6	304	0 45	6 58 21	91	25 27·8	34	6 57
Tues.	**24**	0 49 40	273	4 8·0	303	0 45	6 59 52	92	25 24·4	35	6 55
Wed.	**25**	0 54 13	273	4 38·3	303	0 46	7 1 24	94	25 20·9	36	6 52
Thur.	**26**	0 58 46	273	5 8·6	301	0 46	7 2 58	95	25 17·3	37	6 50
Frid.	**27**	1 3 19	274	5 38·7	300	0 47	7 4 33	96	25 13·6	37	6 48
Sat.	**28**	1 7 53	274	6 8·7	299	0 48	7 6 9	97	25 9·9	38	6 45
Sun.	**29**	1 12 27	275	6 38·6	297	0 48	7 7 46	99	25 6·1	39	6 43
Mon.	**30**	1 17 2	275	7 8·3	295	0 49	7 9 25	100	25 2·2	40	6 41
Tues.	**31**	1 21 37	276	7 37·8	294	0 50	7 11 5	101	24 58·2	41	6 38
Wed.	**32**	1 26 13		N. 8 7·2		0 50	7 12 46		N.24 54·1		6 36

MARCH, 1914.

MEAN TIME.

		JUPITER.					SATURN.				
		At Greenwich Mean Noon.				Meridian Passage.	At Greenwich Mean Noon.				Meridian Passage.
		R.A.		Dec.			R.A.		Dec.		
		h m s		° ′		h m	h m s		° ′		h m
Sun.	**1**	20 46 3	54	S. 18 27·9	33	22 9	4 40 43	8	N. 20 44·5	5	6 6
Mon.	**2**	20 46 57	53	18 24·6	34	22 6	4 40 51	9	20 45·0	5	6 2
Tues.	**3**	20 47 50	53	18 21·2	33	22 3	4 41 0	9	20 45·5	5	5 58
Wed.	**4**	20 48 43	53	18 17·9	33	22 0	4 41 9	10	20 46·0	6	5 55
Thur.	**5**	20 49 36	52	18 14·6	34	21 57	4 41 19	10	20 46·6	6	5 51
Frid.	**6**	20 50 28	52	18 11·2	33	21 54	4 41 29	11	20 47·2	5	5 47
Sat.	**7**	20 51 20	52	18 7·9	33	21 51	4 41 40	11	20 47·7	6	5 43
Sun.	**8**	20 52 12	52	18 4·6	34	21 48	4 41 51	12	20 48·3	6	5 40
Mon.	**9**	20 53 4	51	18 1·2	33	21 45	4 42 3	12	20 48·9	6	5 36
Tues.	**10**	20 53 55	51	17 57·9	33	21 42	4 42 15	12	20 49·5	7	5 32
Wed.	**11**	20 54 46	51	17 54·6	33	21 39	4 42 27	13	20 50·2	6	5 28
Thur.	**12**	20 55 37	50	17 51·3	33	21 36	4 42 40	14	20 50·8	6	5 25
Frid.	**13**	20 56 27	50	17 48·0	33	21 33	4 42 54	13	20 51·4	7	5 21
Sat.	**14**	20 57 17	50	17 44·7	33	21 29	4 43 7	15	20 52·1	7	5 17
Sun.	**15**	20 58 7	50	17 41·4	33	21 26	4 43 22	14	20 52·8	6	5 14
Mon.	**16**	20 58 57	49	17 38·1	32	21 23	4 43 36	15	20 53·4	7	5 10
Tues.	**17**	20 59 46	49	17 34·9	33	21 20	4 43 51	16	20 54·1	7	5 6
Wed.	**18**	21 0 35	48	17 31·6	33	21 17	4 44 7	15	20 54·8	7	5 3
Thur.	**19**	21 1 23	48	17 28·3	32	21 14	4 44 22	17	20 55·5	8	4 59
Frid.	**20**	21 2 11	48	17 25·1	32	21 11	4 44 39	16	20 56·3	7	4 55
Sat.	**21**	21 2 59	47	17 21·9	32	21 8	4 44 55	17	20 57·0	7	4 52
Sun.	**22**	21 3 46	48	17 18·7	32	21 4	4 45 12	18	20 57·7	7	4 48
Mon.	**23**	21 4 34	46	17 15·5	32	21 1	4 45 30	17	20 58·4	8	4 44
Tues.	**24**	21 5 20	47	17 12·3	32	20 58	4 45 47	18	20 59·2	8	4 41
Wed.	**25**	21 6 7	46	17 9·1	31	20 55	4 46 5	19	21 0·0	7	4 37
Thur.	**26**	21 6 53	45	17 6·0	32	20 52	4 46 24	19	21 0·7	8	4 33
Frid.	**27**	21 7 38	45	17 2·8	31	20 49	4 46 43	19	21 1·5	8	4 30
Sat.	**28**	21 8 23	45	16 59·7	31	20 45	4 47 2	20	21 2·3	7	4 26
Sun.	**29**	21 9 8	45	16 56·6	31	20 42	4 47 22	20	21 3·0	8	4 23
Mon.	**30**	21 9 53	43	16 53·5	30	20 39	4 47 42	20	21 3·8	8	4 19
Tues.	**31**	21 10 36	44	16 50·5	31	20 36	4 48 2	21	21 4·6	8	4 15
Wed.	**32**	21 11 20		S. 16 47·4		20 33	4 48 23		N. 21 5·4		4 12

APRIL, 1914.

AT GREENWICH MEAN NOON.

THE SUN.

Date.		Declination.	Var. in 1 hour.	Semi-diameter.	Equation of Time *Add to* / *Subtract from Apparent Time.*	Var. in 1 hour.	Right Ascension of the Mean Sun (*Sidereal Time*).
		° ′	′	′ ″	m s	s	h m s
Wed.	**1**	N. 4 19·5	0·97	16 2	4 8·9	0·75	0 36 0·2
Thur.	**2**	4 42·6	0·96	16 1	3 50·8	0·75	0 39 56·8
Frid.	**3**	5 5·7	0·96	16 1	3 32·9	0·75	0 43 53·3
Sat.	**4**	N. 5 28·7	0·96	16 1	3 15·0	0·74	0 47 49·9
Sun.	**5**	5 51·6	0·95	16 1	2 57·3	0·74	0 51 46·4
Mon.	**6**	6 14·3	0·95	16 0	2 39·8	0·73	0 55 43·0
Tues.	**7**	N. 6 37·0	0·94	16 0	2 22·4	0·72	0 59 39·5
Wed.	**8**	6 59·5	0·94	16 0	2 5·2	0·71	1 3 36·1
Thur.	**9**	7 22·0	0·93	15 59	1 48·2	0·70	1 7 32·6
Frid.	**10**	N. 7 44·3	0·93	15 59	1 31·5	0·69	1 11 29·2
Sat.	**11**	8 6·5	0·92	15 59	1 15·0	0·68	1 15 25·7
Sun.	**12**	8 28·5	0·92	15 59	0 58·8	0·67	1 19 22·3
Mon.	**13**	N. 8 50·4	0·91	15 58	0 42·9	0·66	1 23 18·9
Tues.	**14**	9 12·2	0·90	15 58	0 27·4	0·64	1 27 15·4
Wed.	**15**	9 33·8	0·90	15 58	0 12·1	0·63	1 31 12·0
Thur.	**16**	N. 9 55·2	0·89	15 58	0 2·7	0·61	1 35 8·5
Frid.	**17**	10 16·5	0·88	15 57	0 17·2	0·60	1 39 5·1
Sat.	**18**	10 37·6	0·88	15 57	0 31·3	0·58	1 43 1·6
Sun.	**19**	N.10 58·6	0·87	15 57	0 45·0	0·56	1 46 58·2
Mon.	**20**	11 19·3	0·86	15 56	0 58·3	0·54	1 50 54·7
Tues.	**21**	11 39·9	0·85	15 56	1 11·1	0·53	1 54 51·3
Wed.	**22**	N.12 0·3	0·85	15 56	1 23·5	0·51	1 58 47·9
Thur.	**23**	12 20·5	0·84	15 56	1 35·4	0·49	2 2 44·4
Frid.	**24**	12 40·5	0·83	15 55	1 46·9	0·47	2 6 41·0
Sat.	**25**	N.13 0·3	0·82	15 55	1 57·9	0·45	2 10 37·5
Sun.	**26**	13 19·9	0·81	15 55	2 8·5	0·43	2 14 34·1
Mon.	**27**	13 39·2	0·80	15 55	2 18·5	0·41	2 18 30·6
Tues.	**28**	N.13 58·4	0·79	15 54	2 28·1	0·39	2 22 27·2
Wed.	**29**	14 17·2	0·78	15 54	2 37·1	0·37	2 26 23·7
Thur.	**30**	14 35·9	0·77	15 54	2 45·7	0·35	2 30 20·3
Frid.	**31**	N.14 54·3	0·76	15 54	2 53·7	0·32	2 34 16·8

Add for hours.

m s	h
0 9·9	1
0 19·7	2
0 29·6	3
0 39·4	4
0 49·3	5
0 59·1	6
1 9·0	7
1 18·9	8
1 28·7	9
1 38·6	10
1 48·4	11
1 58·3	12
2 8·1	13
2 18·0	14
2 27·8	15
2 37·7	16
2 47·6	17
2 57·4	18
3 7·3	19
3 17·1	20
3 27·0	21
3 36·8	22
3 46·7	23
3 56·6	24

Add for minutes.

s	m
0·2	1
0·3	2
0·5	3
0·7	4
0·8	5
1·0	6
1·1	7
1·3	8
1·5	9
1·6	10
3·3	20
4·9	30
6·6	40
8·2	50

APRIL, 1914.

MEAN TIME.

Date.		Transit of the First Point of Aries.	THE MOON.								
			Semi-diameter.	Var. in 1 hour.	Horizontal Parallax.	Var. in 1 hour.	Meridian Passage.				Age.
			Noon.		Noon.		Upper.	Diff.	Lower.	Diff.	Noon.
		h m s	′ ″	″	′ ″	″	h m	m	h m	m	d
Wed.	**1**	23 20 9·8	15 4	0·4	55 10	1·4	4 21	54	16 48	55	5·7
Thur.	**2**	23 16 13·9	15 14	0·5	55 47	1·7	5 15	56	17 43	56	6·7
Frid.	**3**	23 12 18·0	15 26	0·5	56 32	2·0	6 11	56	18 39	55	7·7
Sat.	**4**	23 8 22·1	15 40	0·6	57 23	2·2	7 7	54	19 34	54	8·7
Sun.	**5**	23 4 26·2	15 55	0·7	58 19	2·4	8 1	53	20 28	51	9·7
Mon.	**6**	23 0 30·3	16 10	0·6	59 16	2·3	8 54	51	21 19	51	10·7
Tues.	**7**	22 56 34·3	16 25	0·5	60 8	2·0	9 45	51	22 10	51	11·7
Wed.	**8**	22 52 38·4	16 36	0·4	60 51	1·5	10 36	51	23 1	53	12·7
Thur.	**9**	22 48 42·5	16 44	0·2	61 18	0·7	11 27	54	23 54	54	13·7
Frid.	**10**	22 44 46·6	16 46	0·0	61 26	0·1	12 21	56	* *		14·7
Sat.	**11**	22 40 50·7	16 43	0·2	61 14	0·9	13 17	61	0 48	59	15·7
Sun.	**12**	22 36 54·8	16 35	0·4	60 44	1·6	14 18	61	1 47	61	16·7
Mon.	**13**	22 32 58·9	16 22	0·6	59 58	2·1	15 19	62	2 48	62	17·7
Tues.	**14**	22 29 3·0	16 7	0·6	59 4	2·3	16 21	59	3 50	61	18·7
Wed.	**15**	22 25 7·1	15 52	0·7	58 6	2·4	17 20	55	4 51	57	19·7
Thur.	**16**	22 21 11·2	15 36	0·6	57 10	2·2	18 15	51	5 48	53	20·7
Frid.	**17**	22 17 15·3	15 22	0·5	56 19	2·0	19 6	46	6 41	48	21·7
Sat.	**18**	22 13 19·4	15 10	0·5	55 35	1·7	19 52	42	7 29	44	22·7
Sun.	**19**	22 9 23·4	15 0	0·4	54 59	1·3	20 34	40	8 13	41	23·7
Mon.	**20**	22 5 27·5	14 53	0·3	54 32	1·0	21 14	39	8 54	40	24·7
Tues.	**21**	22 1 31·6	14 48	0·2	54 13	0·6	21 53	39	9 34	38	25·7
Wed.	**22**	21 57 35·7	14 45	0·1	54 1	0·3	22 32	40	10 12	40	26·7
Thur.	**23**	21 53 39·8	14 43	0·0	53 57	0·1	23 12	41	10 52	40	27·7
Frid.	**24**	21 49 43·9	14 44	0·1	53 58	0·2	23 53	45	11 32	43	28·7
Sat.	**25**	21 45 48·0	14 46	0·1	54 5	0·4	* *		12 15	46	0·0
Sun.	**26**	21 41 52·1	14 49	0·2	54 17	0·6	0 38	48	13 1	50	1·0
Mon.	**27**	21 37 56·2	14 54	0·2	54 34	0·8	1 26	51	13 51	52	2·0
Tues.	**28**	21 34 0·3	15 0	0·3	54 56	1·0	2 17	53	14 43	55	3·0
Wed.	**29**	21 30 4·3	15 7	0·4	55 23	1·3	3 10	55	15 38	55	4·0
Thur.	**30**	21 26 8·4	15 16	0·4	55 56	1·5	4 5	55	16 33	54	5·0
Frid.	**31**	21 22 12·5	15 26	0·5	56 34	1·7	5 0		17 27		6·0

G.M.T.

THE SUN.

	Saturday 25			**Tuesday 28**		
	R.A.M.S.	Dec.	Equation of Time.	R.A.M.S.	Dec.	Equation of Time.
h	h m s	° ′	m s	h m s	° ′	m s
0	2 10 37·5	N. 13 0·3	— 1 57·9	2 22 27·2	N. 13 58·4	— 2 28·1
2	2 10 57·2	13 1·9	1 58·8	2 22 46·9	14 0·0	2 28·9
4	2 11 16·9	13 3·6	1 59·7	2 23 6·6	14 1·5	2 29·6
6	2 11 36·6	13 5·2	2 0·6	2 23 26·3	14 3·1	2 30·4
8	2 11 56·4	13 6·8	2 1·5	2 23 46·1	14 4·7	2 31·1
10	2 12 16·1	13 8·5	2 2·3	2 24 5·8	14 6·2	2 31·9
12	2 12 35·8	13 10·1	2 3·2	2 24 25·5	14 7·8	2 32·6
14	2 12 55·5	13 11·7	2 4·1	2 24 45·2	14 9·4	2 33·4
16	2 13 15·2	13 13·4	2 5·0	2 25 4·9	14 10·9	2 34·1
18	2 13 35·0	13 15·0	2 5·9	2 25 24·6	14 12·5	2 34·9
20	2 13 54·7	13 16·6	2 6·8	2 25 44·3	14 14·1	2 35·6
22	2 14 14·4	13 18·3	2 7·6	2 26 4·0	14 15·6	2 36·4
	Sunday 26			**Wednesday 29**		
0	2 14 34·1	N. 13 19·9	— 2 8·5	2 26 23·7	N. 14 17·2	— 2 37·1
2	2 14 53·8	13 21·5	2 9·3	2 26 43·4	14 18·8	2 37·8
4	2 15 13·5	13 23·2	2 10·2	2 27 3·1	14 20·3	2 38·6
6	2 15 33·2	13 24·8	2 11·0	2 27 22·8	14 21·9	2 39·3
8	2 15 53·0	13 26·4	2 11·8	2 27 42·6	14 23·5	2 40·0
10	2 16 12·7	13 28·0	2 12·7	2 28 2·3	14 25·0	2 40·7
12	2 16 32·4	13 29·6	2 13·5	2 28 22·0	14 26·6	2 41·4
14	2 16 52·1	13 31·2	2 14·3	2 28 41·7	14 28·2	2 42·1
16	2 17 11·8	13 32·8	2 15·2	2 29 1·4	14 29·7	2 42·9
18	2 17 31·5	13 34·4	2 16·0	2 29 21·2	14 31·3	2 43·6
20	2 17 51·2	13 36·0	2 16·8	2 29 40·9	14 32·8	2 44·3
22	2 18 10·9	13 37·6	2 17·7	2 30 0·6	14 34·4	2 45·0
	Monday 27			**Thursday 30**		
0	2 18 30·6	N. 13 39·2	— 2 18·5	2 30 20·3	N. 14 35·9	— 2 45·7
2	2 18 50·3	13 40·8	2 19·3	2 30 40·0	14 37·4	2 46·4
4	2 19 10·0	13 42·4	2 20·1	2 30 59·7	14 39·0	2 47·0
6	2 19 29·7	13 44·0	2 20·9	2 31 19·4	14 40·5	2 47·7
8	2 19 49·5	13 45·6	2 21·7	2 31 39·2	14 42·0	2 48·4
10	2 20 9·2	13 47·2	2 22·5	2 31 58·9	14 43·6	2 49·0
12	2 20 28·9	13 48·8	2 23·3	2 32 18·6	14 45·1	2 49·7
14	2 20 48·6	13 50·4	2 24·1	2 32 38·3	14 46·6	2 50·4
16	2 21 8·3	13 52·0	2 24·9	2 32 58·0	14 48·2	2 51·0
18	2 21 28·1	13 53·6	2 25·7	2 33 17·7	14 49·7	2 51·7
20	2 21 47·8	13 55·2	2 26·5	2 33 37·4	14 51·2	2 52·4
22	2 22 7·5	13 56·8	2 27·3	2 33 57·1	14 52·8	2 53·0
24	2 22 27·2	N. 13 58·4	— 2 28·1	2 34 16·8	N. 14 54·3	— 2 53·7

The R.A. of Mer. (local Sidereal Time) is found by adding the Right Ascension of the Mean Sun to the local Mean Time. The signs ± under Equation of Time denote *additive* or *subtractive* to Apparent Time and vice versâ to Mean Time.

Date.	α Aurigæ. (*Capella*) 0·2		α Orionis. (*Betel.*) 1·0–1·4		α Argûs. (*Canopus*) –1·0		α Can. Min. (*Procyon*) 0·5		α Leonis. (*Regulus*) 1·3		α Ursæ Mag. (*Dubhe*) 2·0	
	R.A.	Dec. N.	R.A.	Dec. N.	R.A.	Dec. S.	R.A.	Dec. N.	R.A.	Dec. N.	R.A.	Dec. N.
	h m 5 10 s	° 45 ′	h m 5 50 s	° 7 ′	h m 6 22 s	° 52 ′	h m 7 34 s	° 5 ′	h m 10 3 s	° 12 ′	h m 10 58 s	° 62 ′
Jan. **1** -	22·1	54·9	32·5	23·6	4·8	38·8	49·6	26·8	48·9	23·2	28·5	12·7
April **1** -	20·6	55·0	31·7	23·6	2·7	39·1	49·3	26·7	49·8	23·2	30·7	12·9
June **30** -	20·8	54·8	31·6	23·7	1·1	38·8	48·7	26·8	48·9	23·2	28·1	13·1
Sept. **28** -	24·4	54·8	34·0	23·8	3·7	38·5	50·4	26·9	49·5	23·2	27·8	12·6
Dec. **27** -	26·9	55·0	36·1	23·6	6·3	38·8	53·0	26·7	52·2	22·9	32·2	12·3

APPENDIX B.

DAILY WEATHER REPORT OF THE METEOROLOGICAL OFFICE.

CHANGE OF UNITS OF MEASUREMENTS.

Barometric Pressure in Pressure Units.

In their Eighth Report to the Lords Commissioners of His Majesty's Treasury, the Meteorological Committee intimated their intention to use Absolute Units for pressure in the Daily Weather Report of the Meteorological Office from 1st May, 1914.

The absolute unit of pressure on the the Centimetre-Gramme-Second system* is the dyne per square centimetre. As this unit is exceedingly small a practical unit one million times as great has been suggested. This unit, the megadyne per square centimetre, is called a "bar." In the Daily Weather Report the centibar and the millibar, respectively, the hundredth and the thousandth part of the "bar" are adopted as working units. The relation between the millibar and the inch of mercury is given in the tables overleaf.

Reasons for the Change.

One of the principal reasons for this change is that it is a step towards the adoption of a system of units which may become common to all nations.

The system was approved by the Meteorological Council in 1904 and by the Gassiot Committee of the Royal Society in 1910. Upon the initiative of Professor V. Bjerknes, formerly professor at Christiania, and now of the Geophysical Institute at Leipzig, it was used in important publications of the Carnegie Institution of Washington, and was adopted by the International Commission for Scientific Aeronautics for the international publication of the results of the investigation of the upper air. Since 1907 the system has been used in the Meteorological Office for the upper air, and since 1911 for the data from the Observatories where Centimetre-Grand-Second units have been used for many years in connection with magnetism and electricity. The Weather Bureau of the United States has adopted *millibars* and *absolute temperatures* on the Centigrade Scale for the issue of daily charts of the Northern Hemisphere, which began on 1st January, 1914; the Royal Meteorological Society has decided to use *millibars* for the expression of the series of pressure normals for the British Isles, which it is now preparing; and the Meteorological Office has followed the example of the Weather Bureau in using absolute units for the daily maps in the Weekly Weather Report, but its isobars are figured in centibars as they were in the specimen issued with the Eighth Annual Report.

---

* Particulars of the Centimetre-Gramme-Second system are given in the *Observer's Handbook,* 1913 edition.

The Scientific Appeal.

The ground of scientific appeal to all nations to adopt the bar, centibar, and millibar is that these units fall naturally into place as members of the Centimetre-Gramme-Second system of units which has already become universal for Magnetism and Electricity and most branches of Physics. Its principles are therefore well known. The inch and the millimetre are really units of length, and to estimate the effect of a pressure measured in terms of height of a column of mercury it is necessary to introduce the value of the density of mercury at some particular temperature, and the value of the acceleration due to gravity at a particular place. It is well known that the atmospheric pressure at sea level in Britain varies between 13¾ and 15¼ lbs. weight per square inch. The pound weight per square inch is often used by engineers, but it is not a convenient unit because its value depends upon latitude.

The Upper Air.

The past fifteen years have witnessed the collection of extensive meteorological observations in the upper air made by means of kites and balloons, from which important results have already been deduced. The absolute system of units is the most convenient for the discussion of the data so collected, and it is being generally adopted for the purpose. The rapid development of aviation makes it impossible to draw a line between the academic study of the meteorology of the upper air and the practical meteorology of the Daily Weather Report. The use of two systems of units, one for observations made at the surface, and the other for observations taken at higher levels, could only retard progress.

Practical Considerations.

It is acknowledged that an accuracy of one thousandth of an inch is not really attainable in practice. For many years the Inspectors of the Meteorological Office have had to be satisfied with agreement within ·003 in., and now the National Physical Laboratory has ceased to certify barometers of the Kew pattern to the thousandth of an inch. Consequently with an instrument graduated to ·001 in., observers are being asked to read to an accuracy which is acknowledged to be unattainable. On the other hand an accuracy of the hundredth of an inch is not good enough for scientific purposes.

The practical degree of precision for a mercury barometer of the Kew type is *one-tenth of a millibar.* Graduation in centibars and millibars, with a simple vernier scale for estimating to tenths of a millibar, thus brings the demand for accuracy made upon the observer into harmony with that actually attainable. The new graduation does away with the complications of the conventional vernier scale in use on barometers graduated in inches, and consequently the risk of errors of observation is reduced.

The Percentage Barometer.

Another advantage is that the Bar, or Centimetre-Gramme-Second atmosphere, differs but little from the standard atmosphere. The equivalent of the adopted normal value at sea level of 29·92 mercury inches is 101·32 centibars, or 1013·2 millibars. The lowest barometer value ever observed for sea level in the British Isles is 925·5 millibars, the equivalent of 27·33 inches. This value was recorded at Ochtertyre on January 26th, 1884. The highest value is 1053·5 millibars, the equivalent of 31·11 mercury inches. It was recorded at Aberdeen on January 31st, 1902.

A reading of 100 centibars, or 1,000 millibars, is equivalent to 29·53 mercury inches. It will be remembered that the word "change" is placed opposite the sea-level reading 29·5 in the conventional descriptions engraved on dial barometers. Thus in a barometer graduated in centibars the reading 100 would occupy the position conventionally marked "change."

Practical Course to be pursued.

It is evidently impossible at one operation to change all the barometers in use in the various services, and even in the most favourable circumstances there must be for many observers a time when the readings are taken on one scale, and the results quoted or published in another. Tables of equivalents are given herewith for making the necessary conversion.

The barometers issued by the Meteorological Office will be graduated in both scales.[*]

RAINFALL DATA IN MILLIMETRES.

As a further step in the direction of international uniformity all rainfall data will be published in the Daily Weather Report in millimetres instead of inches. The occasion for making the change is that modifications are being introduced into the telegraphic code used for the exchange of meteorological information in Europe.

---

[*] It should be borne in mind that the inch scale is graduated to be correct at 62° F., the millibar scale at the temperature of the freezing point, 32° F. When both scales are at the same temperature the relation between them is that shown in the conversion tables corrected by the subtraction of 0·3 millibar, *e.g.*, the graduation 28·0 inch should agree with the graduation 948·2–·3 or 947·9 millibars.

The reading of rainfall in this country has been carried to hundredths, sometimes to thousandths of an inch, but the readings to the higher degree of accuracy have seldom any practical meaning. The readings on the metric system are carried to 0·1 millimetre, 0·004 inch, which represents satisfactorily the highest degree of accuracy. The range is from ·01 to 3, 4, or even more inches in exceptional circumstances, for a day's rain. The telegraphic code hitherto in use has made provision for reporting amounts up to 10 inches, though the large majority of the readings are under 2 inches. The code now to be introduced makes provision for reporting amounts up to 100 millimetres or 4 inches.

As one inch is approximately equivalent to 25 millimetres the conversion from millimetres to inches, or *vice versâ*, may be made with sufficient accuracy for most purposes by multiplying or dividing by 4 and appropriately shifting the decimal point. Tables of conversion are given herewith.

Wind Velocities in Metres per Second.

Wind force will be specified on the Beaufort scale. Occasional reports are received from anemometer stations regarding the extreme wind velocities attained in gales. These data are published on the front page of the report. The unit of wind velocity used in such cases will be the *metre per second*. Tables for converting velocities from miles per hour to metres per second, or *vice versâ*, are given below.

Meteorological Office,
London, S.W.,
April, 1914.

W. N. SHAW,
Director.

CONVERSION TABLES.

Pressure Values.

Equivalents in Millibars of Inches of Mercury at 32° and Latitude 45°.

Mercury Inches.	·00	·01	·02	·03	·04	·05	·06	·07	·08	·09
	Millibars.									
27·0	914·3	914·6	915·0	915·3	915·7	916·0	916·3	916·7	917·0	917·4
27·1	917·7	918·0	918·4	918·7	919·0	919·4	919·7	920·1	920·4	920·7
27·2	921·1	921·4	921·8	922·1	922·4	922·8	923·1	923·4	923·8	924·1
27·3	924·5	924·8	925·1	925·5	925·8	926·1	926·5	926·8	927·2	927·5
27·4	927·9	928·2	928·5	928·9	929·2	929·5	929·9	930·2	930·6	930·9
27·5	931·2	931·6	931·9	932·3	932·6	932·9	933·3	933·6	933·9	934·3
27·6	934·6	935·0	935·3	935·6	936·0	936·3	936·7	937·0	937·3	937·7
27·7	938·0	938·3	938·7	939·0	939·4	939·7	940·0	940·4	940·7	941·1
27·8	941·4	941·7	942·1	942·4	942·8	943·1	943·4	943·8	944·1	944·4
27·9	944·8	945·1	945·5	945·8	946·1	946·5	946·8	947·2	947·5	947·8
28·0	948·2	948·5	948·8	949·2	949·5	949·9	950·2	950·5	950·9	951·2
28·1	951·6	951·9	952·2	952·6	952·9	953·2	953·6	953·9	954·3	954·6
28·2	954·9	955·3	955·6	956·0	956·3	956·6	957·0	957·3	957·7	958·0
28·3	958·3	958·7	959·0	959·3	959·7	960·0	960·4	960·7	961·0	961·4
28·4	961·7	962·1	962·4	962·7	963·1	963·4	963·7	964·1	964·4	964·8
28·5	965·1	965·4	965·8	966·1	966·5	966·8	967·1	967·5	967·8	968·1
28·6	968·5	968·8	969·2	969·5	969·8	970·2	970·5	970·9	971·2	971·5
28·7	971·9	972·2	972·6	972·9	973·2	973·6	973·9	974·2	974·6	974·9
28·8	975·3	975·6	975·9	976·3	976·6	977·0	977·3	977·6	978·0	978·3
28·9	978·6	979·0	979·3	979·7	980·0	980·3	980·7	981·0	981·4	981·7
29·0	982·0	982·4	982·7	983·0	983·4	983·7	984·1	984·4	984·7	985·1
29·1	985·4	985·8	986·1	986·4	986·8	987·1	987·5	987·8	988·1	988·5
29·2	988·8	989·1	989·5	989·8	990·2	990·5	990·8	991·2	991·5	991·9
29·3	992·2	992·5	992·9	993·2	993·5	993·9	994·2	994·6	994·9	995·2
29·4	995·6	995·9	996·3	996·6	996·9	997·3	997·6	997·9	998·3	998·6
29·5	999·0	999·3	999·6	1000·0	1000·3	1000·7	1001·0	1001·3	1001·7	1002·0
29·6	1002·4	1002·7	1003·0	1003·4	1003·7	1004·0	1004·4	1004·7	1005·1	1005·4
29·7	1005·7	1006·1	1006·4	1006·8	1007·1	1007·4	1007·8	1008·1	1008·4	1008·8
29·8	1009·1	1009·5	1009·8	1010·1	1010·5	1010·8	1011·2	1011·5	1011·8	1012·2
29·9	1012·5	1012·8	1013·2	1013·5	1013·9	1014·2	1014·5	1014·9	1015·2	1015·6
30·0	1015·9	1016·2	1016·6	1016·9	1017·3	1017·6	1017·9	1018·3	1018·6	1018·9
30·1	1019·3	1019·6	1020·0	1020·3	1020·6	1021·0	1021·3	1021·7	1022·0	1022·3
30·2	1022·7	1023·0	1023·3	1023·7	1024·0	1024·4	1024·7	1025·0	1025·4	1025·7
30·3	1026·1	1026·4	1026·7	1027·1	1027·4	1027·7	1028·1	1028·4	1028·8	1029·1
30·4	1029·4	1029·8	1030·1	1030·5	1030·8	1031·1	1031·5	1031·8	1032·2	1032·5
30·5	1032·8	1033·2	1033·5	1033·8	1034·2	1034·5	1034·9	1035·2	1035·5	1035·9
30·6	1036·2	1036·6	1036·9	1037·2	1037·6	1037·9	1038·2	1038·6	1038·9	1039·3
30·7	1039·6	1039·9	1040·3	1040·6	1041·0	1041·3	1041·6	1042·0	1042·3	1042·6
30·8	1043·0	1043·3	1043·7	1044·0	1044·3	1044·7	1045·0	1045·4	1045·7	1046·0
30·9	1046·4	1046·7	1047·1	1047·4	1047·7	1048·1	1048·4	1048·7	1049·1	1049·4

Equivalents in Mercury Inches at 32° and Latitude 45° of Millibars.

Milli-bars.	0	1	2	3	4	5	6	7	8	9
	Mercury Inches.									
910	26·87	26·90	26·93	26·96	26·99	27·02	27·05	27·08	27·11	27·14
920	27·17	27·20	27·23	27·26	27·29	27·32	27·35	27·38	27·41	27·44
930	27·46	27·49	27·52	27·55	27·58	27·61	27·64	27·67	27·70	27·73
940	27·76	27·79	27·82	27·85	27·88	27·91	27·94	27·97	28·00	28·03
950	28·05	28·08	28·11	28·14	28·17	28·20	28·23	28·26	28·29	28·32
960	28·35	28·38	28·41	28·44	28·47	28·50	28·53	28·56	28·59	28·62
970	28·65	28·67	28·70	28·73	28·76	28·79	28·82	28·85	28·88	28·91
980	28·94	28·97	29·00	29·03	29·06	29·09	29·12	29·15	29·18	29·21
990	29·24	29·26	29·29	29·32	29·35	29·38	29·41	29·44	29·47	29·50
1000	29·53	29·56	29·59	29·62	29·65	29·68	29·71	29·74	29·77	29·80
1010	29·83	29·86	29·89	29·92	29·94	29·97	30·00	30·03	30·06	30·09
1020	30·12	30·15	30·18	30·21	30·24	30·27	30·30	30·33	30·36	30·39
1030	30·42	30·45	30·48	30·51	30·53	30·56	30·59	30·62	30·65	30·68
1040	30·71	30·74	30·77	30·80	30·83	30·86	30·89	30·92	30·95	30·98
1050	31·01	31·04	31·07	31·10	31·13	31·16	31·18	31·21	31·24	31·27

Differences for tenths of a millibar :—

mb.	·1	·2	·3	·4	·5	·6	·7	·8	·9
in.	·003	·006	·009	·012	·015	·018	·021	·024	·027

RAINFALL VALUES.

Equivalents in Millimetres of Inches.

1 inch = 25·4 Millimetres.

Inches.	·00	·01	·02	·03	·04	·05	·06	·07	·08	·09
	Millimetres.									
00	0·0	0·3	0·5	0·8	1·0	1·3	1·5	1·8	2·0	2·3
·10	2·5	2·8	3·1	3·3	3·6	3·8	4·1	4·3	4·6	4·8
·20	5·1	5·3	5·6	5·8	6·1	6·4	6·6	6·9	7·1	7·4
·30	7·6	7·9	8·1	8·4	8·6	8·9	9·1	9·4	9·7	9·9
·40	10·2	10·4	10·7	10·9	11·2	11·4	11·7	11·9	12·2	12·5
·50	12·7	13·0	13·2	13·5	13·7	14·0	14·2	14·5	14·7	15·0
·60	15·2	15·5	15·8	16·0	16·3	16·5	16·8	17·0	17·3	17·5
·70	17·8	18·0	18·3	18·5	18·8	19·1	19·3	19·6	19·8	20·1
·80	20·3	20·6	20·8	21·1	21·3	21·6	21·8	22·1	22·4	22·6
·90	22·9	23·1	23·4	23·6	23·9	24·1	24·4	24·6	24·9	25·2

Equivalents in Inches of Millimetres.

Millimetres.	0	1	2	3	4	5	6	7	8	9
	Inches.									
0	0·00	0·04	0·08	0·12	0·16	0·20	0·24	0·28	0·32	0·35
10	0·39	0·43	0·47	0·51	0·55	0·59	0·63	0·67	0·71	0·75
20	0·79	0·83	0·87	0·91	0·95	0·98	1·02	1·06	1·10	1·14
30	1·18	1·22	1·26	1·30	1·34	1·38	1·42	1·46	1·50	1·54
40	1·58	1·61	1·65	1·69	1·73	1·77	1·81	1·85	1·89	1·93
50	1·97	2·01	2·05	2·09	2·13	2·17	2·21	2·24	2·28	2·32
60	2·36	2·40	2·44	2·48	2·52	2·56	2·60	2·64	2·68	2·72
70	2·76	2·80	2·84	2·87	2·91	2·95	2·99	3·03	3·07	3·11
80	3·15	3·19	3·23	3·27	3·31	3·35	3·39	3·43	3·47	3·50
90	3·54	3·58	3·62	3·66	3·70	3·74	3·78	3·82	3·86	3·90

WIND VELOCITY.

Equivalents of Miles-per-Hour in Metres-per-Second.

Miles per Hour.	0	1	2	3	4	5	6	7	8	9
	Metres per Second.									
0	0·0	0·4	0·9	1·3	1·8	2·2	2·7	3·1	3·6	4·0
10	4·5	4·9	5·4	5·8	6·3	6·7	7·2	7·6	8·0	8·5
20	8·9	9·4	9·8	10·3	10·7	11·2	11·6	12·1	12·5	13·0
30	13·4	13·9	14·3	14·8	15·2	15·6	16·1	16·5	17·0	17·4
40	17·9	18·3	18·8	19·2	19·7	20·1	20·6	21·0	21·5	21·9
50	22·4	22·8	23·2	23·7	24·1	24·6	25·0	25·5	25·9	26·4
60	26·8	27·3	27·7	28·2	28·6	29·1	29·5	30·0	30·4	30·8
70	31·3	31·7	32·2	32·6	33·1	33·5	34·0	34·4	34·9	35·3
80	35·8	36·2	36·7	37·1	37·6	38·0	38·4	38·9	39·3	39·8
90	40·2	40·7	41·1	41·6	42·0	42·5	42·9	43·4	43·8	44·3

Equivalents of Metres-per-Second in Miles-per-Hour.

Metres per Second.	0	1	2	3	4	5	6	7	8	9
	Miles per Hour.									
0	0·0	2·2	4·5	6·7	9·0	11·2	13·4	15·7	17·9	20·1
10	22·4	24·6	26·8	29·1	31·3	33·6	35·8	38·0	40·3	42·5
20	44·7	47·0	49·2	51·5	53·7	55·9	58·2	60·4	62·6	64·9
30	67·1	69·4	71·6	73·8	76·1	78·3	80·5	82·8	85·0	87·2
40	89·5	91·7	94·0	96·2	98·4	100·7	102·9	105·1	107·4	109·6

SPECIFICATION OF THE BEAUFORT SCALE OF WIND FORCE WITH PROBABLE EQUIVALENTS OF THE NUMBERS OF THE SCALE.

Beaufort Number.	General Description of Wind.	Specification of Beaufort Scale.		Mean Wind Force at Standard Density.		Equivalent Velocity in Miles per Hour.†	Limits of Velocities.‡		Beaufort Number.
		For Coast Use, based on Observations made at Scilly, Yarmouth, and Holyhead.	For Use on Land, based on Observations made at Land Stations.	mb.	Lbs. per Sq. Ft.		Statute Miles per Hour.	Metres per Second.	
0	Calm	Calm	Calm; smoke rises vertically	0	0	0	Less than 1	Less than 0·3	0
1	Light air	Fishing smack* just has steerage way.	Direction of wind shown by smoke drift, but not by wind vanes.	·01	·01	2	1–3	0·3–1·5	1
2	Slight breeze	Wind fills the sails of smacks, which then move at about 1–2 miles per hour.	Wind felt on face; leaves rustle; ordinary vane moved by wind.	·04	·08	5	4–7	1·6–3·3	2
3	Gentle breeze	Smacks begin to careen, and travel about 3–4 miles per hour.	Leaves and small twigs in constant motion; wind extends light flag.	·13	·28	10	8–12	3·4–5·4	3
4	Moderate breeze	Good working breeze; smacks carry all canvas, with good list.	Raises dust and loose paper; small branches are moved.	·32	·67	15	13–18	5·5–8·0	4
5	Fresh breeze	Smacks shorten sail	Small trees in leaf begin to sway; crested wavelets form on inland waters.	·62	1·31	21	19–24	8·1–10·7	5
6	Strong breeze	Smacks have double reef in main sail. Care required when fishing.	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty.	1·1	2·3	27	25–31	10·8–13·8	6
7	High wind	Smacks remain in harbour, and those at sea lie to.	Whole trees in motion; inconvenience felt when walking against wind.	1·7	3·6	35	32–38	13·9–17·1	7
8	Gale	All smacks make for harbour, if near.	Breaks twigs off trees; generally impedes progress	2·6	5·4	42	39–46	17·2–20·7	8

9	Strong gale	-	Slight structural damage occurs (chimney pots and slates removed).	3·7	7·7	50	47–54	20·8–24·4	9
10	Whole gale	-	Seldom experienced inland; trees uprooted; considerable structural damage occurs.	5·0	10·5	59	55–63	24·5–28·4	10
11	Storm	-	Very rarely experienced; accompanied by widespread damage.	6·7	14·0	68	64–75	28·5–33·5	11
12	Hurricane	-	-	8·1	Above 17·0	Above 75	Above 75	33·6 and above.	12

* The fishing smack in this column may be taken as representing a trawler of average type and trim. For larger or smaller boats and for special circumstances allowance must be made.

† For converting estimates on the Beaufort scale into miles per hour (anemometer factor, 2·2).
For finding the Beaufort number corresponding to a velocity expressed in miles per hour.

The Beaufort Scale of Weather Notation, as used in the Daily Weather Report.

b = blue sky, *i.e.*, sky quite clear, or not more than a quarter clouded.
bc = sky ¼ to ½ clouded.
c = sky ½ to ¾ clouded.
o = sky overcast, more than three-quarters clouded.
g = gloom.
m = mist.
f = fog.
r = rain.
d = drizzling rain.
e = wet air, without rain falling.
p = passing showers.
h = hail.
s = snow.
t = thunder.
l = lightning.
tl = thunderstorm.
tlr = thunderstorm, accompanied by rain.
q = squalls.
u = ugly threatening sky.
v = visibility, *i.e.*, great transparency, or clearness, of the air, rendering distant objects unusually visible.
w = unusually heavy dew.
x = hoar frost.
z = dust-haze, or smoke.

Scale for Sea Disturbance.

	Description.	Condition of Surface.
0	Calm	Glassy
1	Very smooth	Slightly rippled.
2	Smooth	Rippled.
3	Slight	Rocks buoy, or small boat.
4	Moderate	Furrowed.
5	Rather rough	Much disturbed,
6	Rough	Deeply furrowed.
7	High	Rollers with steep fronts.
8	Very high	Rollers with steep fronts.
9	Phenomenal	Precipitous; towering.

APPENDIX C.

HYDROGRAPHICAL SURVEYING.

1. Introductory.—The method of making a fully detailed survey is exhaustively treated in "Hydrographical Surveying" by Wharton and Field, a copy of which is supplied to each of H.M. Ships; it is extremely rare for such a survey to be undertaken by any Officers other than those who have the full equipment of a surveying vessel at their disposal.

Admiralty charts of nearly all ports and coasts are published, but it should be remembered that few charts are perfect or can remain so for long, on account of the numerous changes which are continually taking place; for example, in the depth of the water due to shifting sands or to dredging, and the erection of new buildings, piers, jetties, &c. In case it should be found that the existing charts of some particular area are incorrect, it is important that the area should be carefully examined. A detailed report of all observations made, together with plans to show any changes which may have taken place since the existing chart was published, should be sent to the Hydrographic Department, in order that the necessary corrections may be made to the chart plate (Manual of Navigation, § 168). In this appendix a brief explanation is given of the various methods of carrying out such an examination.

2. Fixing Objects.—It frequently happens that conspicuous buildings, flagstaffs, &c., which if charted would be useful to navigation, are not shown on the published chart. It is important, when fixing such an object, that its position relatively to the immediately surrounding charted objects should be satisfactorily determined. Various methods may be employed to fix an object. That which gives the most satisfactory results is for the observer to visit some point, the position of which is marked on the chart, and to observe the horizontal angle between some other object which is marked on the chart and the object whose position it is desired to fix. If this operation is repeated at three points and the three lines corresponding to the observed angles are laid off on the chart, their point of intersection will give the position of the object required. In the event of there being only two points marked on the chart from which the object can be seen, it is quite admissible to obtain the third line by an angle observed in the ship, the position of the observer at the time of observation being carefully fixed by means of the station pointer. It is important that all angles should be observed between objects situated at the same level, and the angles should be taken in the horizontal plane. The error due to objects not being at the same level is greatest when the observed angle is small.

When making use of a small angle and any doubt exists as to the objects being at the same level, it is advisable to observe the angle from each object to a third, the latter being so situated as to make a large angle with each of the other objects. The required angle will be the difference between the two angles observed. For example, an observer at O, Fig. 1, wishes to measure the angle AOB. The angles AOC and BOC are measured, C being a distant but well-defined mountain peak, and the angle

$$AOB = AOC - BOC.$$

When selecting the charted objects to which the angles are to be observed the following points should be considered.

The charted object should be as nearly as possible at the same distance from the observer as the object to be fixed.

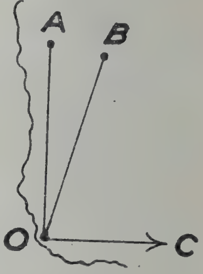


FIG. 1.

The angle should be a horizontal one and should be as small as possible.

Another method is to observe from one point, the position of which is fixed on the chart, the angle between the object to to be fixed and the nearest suitable charted object. A round of angles having been observed at the object it is desired to fix and plotted on a piece of tracing paper, the line corresponding to the first angle observed should be laid off, and then the position should be fixed by means of the angles on the tracing paper; the fix should fall exactly on the line.

Compass bearings should never be used in place of sextant angles for corrections or additions to a chart.

In laying off angles, if great accuracy is required, the method of chords should be adopted.

3. To Lay off an Angle by Means of Chords.—It is required to find the length of a chord which subtends an angle θ at the centre of a circle of radius R. In Fig. 2 let AOB be θ, then AB is the chord whose length is required. From O drop a perpendicular OC on to AB. Then OC bisects the angle AOB, and, therefore, the angle $AOC = \frac{\theta}{2}$.

Now $AB = 2AC = 2R \sin \frac{\theta}{2}$.

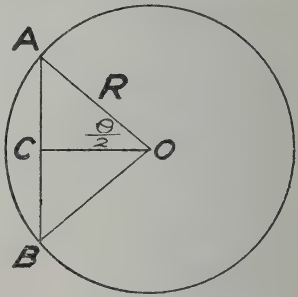


FIG. 2.

Referring to Fig. 3. In order to lay off at the point O a line at an angle θ to the line OD, on OD select a point A

such that $OA = R$, the radius selected. With centre O and radius OA describe the arc of a circle. Having calculated the length of the chord from the above formula, with centre A and the chord as radius, describe the arc of a circle intersecting the previous circle in B. Join OB. Then the angle $BOA = \theta$. The largest radius which can be used should be selected, and the operation should be repeated on DO produced as shown in the figure, not necessarily with the same radius. The three points B', O, and B should all lie in a straight line, which will be a check on the accuracy of the work.

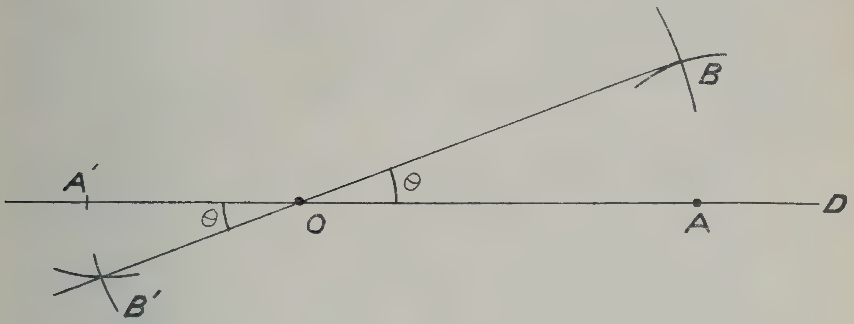


FIG. 3.

4. The Plotting Sheet.—When it is thought that the published chart is inaccurate, either in the soundings or in the coast line, and it is determined to re-examine a particular area, the first consideration should be the method to be adopted in plotting the work. When the existing chart is on a sufficiently large scale and the various conspicuous objects on shore are well charted, the operation is very much simplified. In such a case, having examined the chart and noted all the conspicuous objects, a tracing should be made of those portions of the chart which it is assumed are correct, taking care that all the conspicuous marks are shown. This tracing is then laid on a sheet of paper, and all the conspicuous marks are pricked through. As soon as the tracing paper has been removed a circle should be drawn on the paper round each of these points and their names written against them.

Consideration must now be given as to whether there are sufficient marks on the paper, and whether their relative positions are such as to enable good fixes (Manual of Navigation, § 65) to be obtained from all parts of the area it is proposed to examine. Should there not be sufficient, other conspicuous objects must be fixed as explained in § 2. If insufficient objects exist, it becomes necessary to erect temporary marks and to fix their positions. When making such temporary marks whitewash will be found most useful. A patch of whitewash on a wall or on the sloping surface of a rock, or a small whitewashed cairn of stones, make excellent and conspicuous marks. The size such a mark should be made depends on the distance at which it will be used, and it is better to err on the side of making a mark too large rather than too small. Another type of mark which is frequently useful is a small flagstaff with a parti-coloured flag, one of the colours being white.

When the chart is not on a sufficiently large scale we proceed as follows :—Having noted the conspicuous marks and put up temporary marks as described above, each should be visited. The angles, which are subtended between one distant but well-defined mark (not necessarily one of those selected) and each of the others, should be carefully observed with a sextant. The observations should be written down as shown below, the angles being written to the right or left of the distant mark according to the direction in which they were seen to be situated.

Post	40° 27′	Sharp	50° 45′	Square.
Wood	78 40	(a distant	52 14	Red.
Black	99 03	peak).	75 22	Rock.
Flat	118 37		113 50	Islet.
Tower	120 02			

This method not only facilitates calculating the angle between any two objects, but prevents the cumulative effects of possible uncorrected errors of the sextant, such as if Post were reflected to Wood, Wood to Black, Black to Flat, &c. If possible the round of angles should be completed, and, as 120° is about the limit of angular measurement of any sextant, it is necessary to select another distant but well-defined object and repeat the process, taking care to connect this object with two of the more distant objects of the first series, thus :—

Rock	61° 22′	Flag	22° 10′	Mud.
			67 42	Tree.
			72 18	Sand.
			103 16	Tower.

Then, as a check on the correctness of the whole operation, we have Tower 120° 02′ Sharp 75° 22′ Rock 61° 22′ Flag 103° 16′ Tower, the sum of which angles should equal 360°, or be within a few minutes of it, provided the correct index error has been applied to each angle and the side error taken out.

It is now necessary to place the various marks on the sheet of paper, which is called the plotting sheet, in their correct positions relatively to one another. To do this we select two points, such as *A* and *B*, Fig. 4, as far apart as possible and so situated that two other points *C* and *D*, which are as near the limits of the survey as possible, can be plotted from them by the intersection, at a fairly large angle (60° to 120°), of the two lines which result from plotting the observed angles at *A* and *B*.

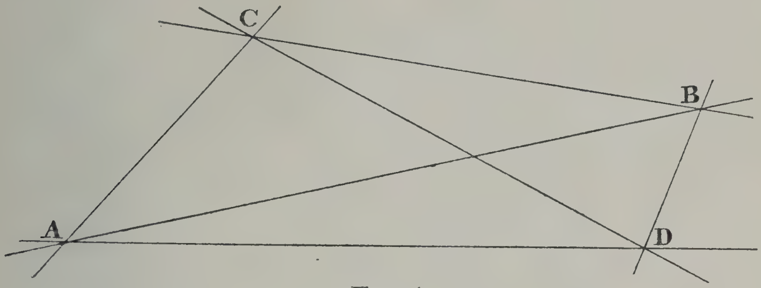


FIG. 4.

Draw a straight pencil line on the plotting sheet to represent *AB*, and, with a needle, prick through the points *A* and *B* at the requisite distance apart depending on the scale on which it is required to make the survey. As a general rule it will be found convenient to make the scale of the survey an exact number of times that of the published chart as this greatly simplifies the comparison of one with the other.

From *A* and *B* lay off the angles to *C* and *D* and then provisionally prick through either *C* or *D*, for choice that one at which the lines intersect most nearly at right angles. In this case we have pricked through *D*; from *D* lay off a line *DC* at the observed angle to *DA*. If now all three lines to *C* intersect at a point, then both *C* and *D* can be pricked through permanently and from the four points *A*, *B*, *C*, and *D*, other points can be plotted. If the three lines through *C* do not intersect exactly, the work should be erased and the operation repeated. The accuracy of the observed angles may be checked by taking the sum of the three angles of each triangle, which should not differ from 180° by more than a few minutes. The remaining points of the survey should now be plotted, each being fixed by the intersection of at least three lines the angles between which are not small. When satisfied with the position of each point it should be pricked through. "Cocked hats" are not admissible because if errors are once accepted they tend to accumulate and will lead to constant trouble. Finally all prick holes should be ringed round in ink.

It may very well happen that the positions of some of the points depend solely on bad or doubtful fixes, and one is not justified in pricking them through; for example they may have at most only two lines intersecting at them, or only two intersecting at a large angle, due to the unavoidable fact that these marks are not visible from a sufficient number of points. In such a case it may be necessary to anchor a boat in a position which can be fixed by sextant angles making use of the points already plotted. An angle may then be taken from the boat to verify the position of the object. This method is frequently made use of for fixing points when there is no difficulty in fixing the boat.

The final scale used is obtained by measuring the distance between two points which can be identified on the chart, and as far apart as possible, and comparing it with the distance as shown on the chart. The true bearing of one of these points from the other should be taken from the chart and a line, to represent a meridian, should be drawn through one of the points on the plotting sheet, at the correct angle to the line joining them.

In the preceding method the scale of the survey has been obtained from the existing chart, and this in most cases will be sufficiently accurate. In some cases, however, the scale cannot be obtained by this method, for it may not be possible to identify any points on the chart, or the chart may be altogether erroneous, or it may be on too small a scale to enable the distance to be measured satisfactorily. It is therefore sometimes necessary actually to measure a distance in order to obtain the scale of the survey. This may be done with sufficient accuracy by quite simple methods, provided the survey does not embrace a very large area.

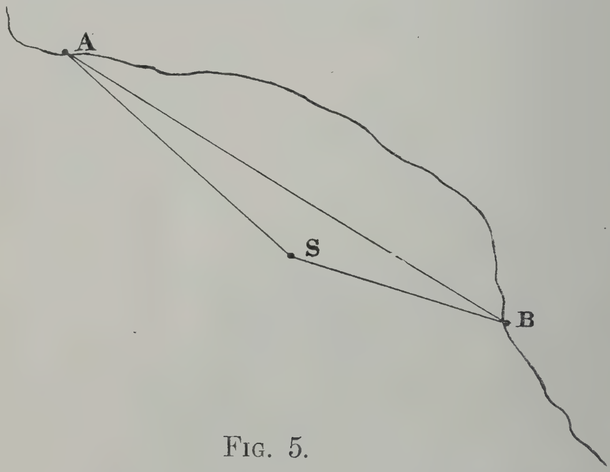


Fig. 5.

Let S, Fig. 5, be the position of the ship at anchor, A and B two points selected so that the angles SAB and ABS are small. The height in feet from the masthead to the waterline having been accurately measured, observers are sent to A and B with sextants. A flag is hoisted at the masthead of the ship and at a pre-arranged time is dipped smartly, at which signal the observers at A and B observe the masthead angle and immediately afterwards the horizontal angles SAB and ABS. If possible two observers should be at both A and B as then both the vertical and horizontal angles can be observed simultaneously. The observations should be repeated at regular intervals as often as considered necessary, but three times is usually sufficient. From each separate series of observations, AS and BS are first calculated from the observed masthead angles, whence

$$AB = AS \cos BAS + BS \cos ABS.$$

Finally the mean is taken of the several values of *AB*, and this distance, represented by the length of *AB* in inches on the plotting sheet, affords a means of obtaining the scale of the survey, provided *A* and *B* are sufficiently far apart to be near the limits of the survey. If, however, the points *A* and *B* are not near or beyond the limits of the area to be surveyed, *AB* should be connected by suitable triangles with two points which are so situated, when the distance apart of these may be calculated by plane trigonometry.

In the method described above, as the angles are all observed simultaneously or nearly so, the movement of the ship as she swings to her anchor makes no practical difference in the final result; and in fact this method may be used even if the ship is under way, provided that her way is stopped for the time being, and that there are two observers at both *A* and *B* to ensure that all angles are observed simultaneously.

Instead of observing the masthead angles at *A* and *B* the distances of *A* and *B* from the ship may be observed by range finder, one distance being observed after the other as quickly as possible when the flag dips, and the angles *SAB* and *SBA* being observed at the same time. This method does not give very accurate results and should only be used if *A* and *B* are suitable objects for range finding; the method by means of masthead angles should generally be used.

It is as well to mention here that the range finder should not be used for general purposes. The main principle of surveying is that the positions of the several points of the survey should be correct relatively to one another, and the positions of the soundings should be correct relatively to those of the points. This result can only be obtained by fixing both points and soundings by angles. A single distance obtained by range finder may or may not be quite accurate, but any such inaccuracy in this case affects the scale of the whole survey, a fact which is of minor importance so long as the points of the survey are relatively correct.

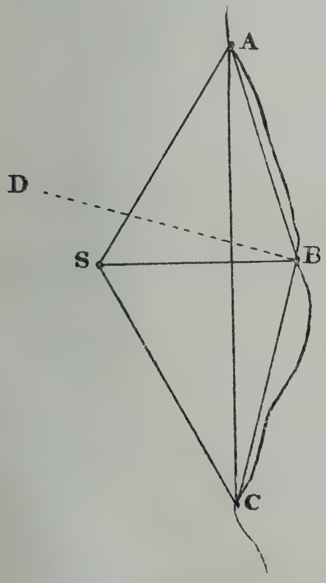


Fig. 6.

Use may be made of the ship for fixing points when they cannot be fixed in the ordinary way. For example, the ship is at anchor at *S*, Fig. 6, and a survey of the anchorage is required. The coast is nearly straight, and *A*, *B*, and *C* are three of the principal points that it is required to fix relatively to each other. Observers having been stationed at A, B, and C and using a system of signals similar to that described above, simultaneous angles are observed as follows:—The observer at A measures the angle BAS, the observer at B measures the angle ABS, and the observer at C measures the angle BCS, the three angles being observed simultaneously; the observations should be repeated three times. The observers at A and C also measure the angles BAC and ACB respectively. The whole angle ABC is also required, but being too large for the observer at B to measure directly, he can wait until either of the other observers joins him. The two observers then measure simultaneously the two angles ABS and SBC, the sum of which is the angle ABC, this observation being repeated two or three times and the mean taken; or the observer at B may be able to make use of a distant fixed object in the direction of D for example, and measure the two angles ABD and DBC; or D may be a floating object provided it is sufficiently far off not to move appreciably whilst the two angles are being observed. It would be advisable in the latter case to repeat the observation of the first angle, observing the angles thus ABD, DBC, ABD and accepting the mean value of ABD. In the event of it being impossible to find a suitable object, some mark on board the ship should be selected as the centre object, the first angle being repeated as before, the whole process repeated several times, and the mean accepted as the correct result. Finally with the angle ABC and the observed value of the angle ABS in each case, the corresponding value of the angle SBC is obtained. Now being given the angles at A and B in the triangle ABS, the angle ASB may be found; given the angles at B and C in the triangle SBC, the angle BSC may be found; then

$$\begin{aligned} BC &= SB \sin BSC \operatorname{cosec} BCS \\ SB &= AB \sin BAS \operatorname{cosec} SAB \\ \text{or } BC &= AB \sin BAS \operatorname{cosec} ASB \sin BSC \operatorname{cosec} BCS. \end{aligned}$$

AB should now be assumed as equal to any convenient number, say 1,000, and the corresponding value of BC may be found.

This process should be repeated three times, using the angles observed at each signal, and from the results the mean value of BC may be obtained relatively to AB.

Now in the triangle ABC drop a perpendicular from B on to AC, then $AC = 1{,}000 \cos BAC + BC \cos ACB$.

We now have the relative values of AB, BC, and AC, and if the actual value of AC be found either by the previous method of masthead angles or taken from the chart, B can be plotted with respect to A and C.

The position of the ship S with regard to A, B, and C is important. It is evident that to obtain the most accurate results the length of SB should not be much less than that of AB

or BC. Theoretically the best position for S with respect to A, B, and C is such that the angle $ABS = SBC$, and the angle $ASC = 180° - ABS$. Naturally the ship cannot always be anchored in the most suitable position, but a boat can be very well used in place of the ship, the same process of signalling by dipping a flag being carried out.

Any number of points, such as A, B, C, D, E, &c., Fig. 7, can be relatively connected in the same way by moving the ship or boat successively to positions S_1, S_2, S_3, &c.

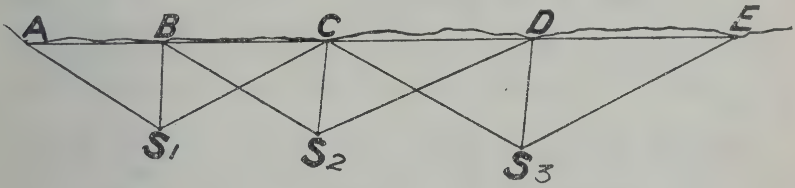


Fig. 7.

With a straight length of coast this may often be the only method available, and with care it is perfectly accurate provided the positions of S_1, S_2, S_3, &c., are suitably selected and the points A, B, C, D, E, &c., are fairly equally separated. It is not necessary for the ship or boat to be actually at anchor provided she is nearly stationary, and that the observations are made simultaneously at the three points.

In the preceding methods it has been suggested that the angle at the ship should be calculated and not directly observed. This will be found to be the most convenient method and the least liable to introduce errors.

5. The Field Board.—In order to preserve the plotting sheet from harm, one or more copies of it are made on sheets of paper which have been previously pasted on to drawing boards. Such a board, on which the various marks are shown and on which all subsequent observations may be plotted at the time of observation, is called a field board. To transfer the various fixed marks from the plotting sheet to the field board, the former is laid over the latter, and is partially covered with weights to keep it quite flat; the various points should then be pricked through, after which they should be ringed round and their names written against them. The area it is proposed to examine should be roughly ringed in pencil, and it is convenient to draw a scale of yards on the board.

6. Sounding.—The value of a chart depends principally on the accuracy of the soundings, and as errors in the depths are not so easily detected as other errors, it is essential that special pains should be taken to obtain and plot the depths of the water accurately. As it is impossible to take a sounding at every point of the bottom it is necessary to adopt some definite plan; this consists of taking the soundings at close intervals along lines, a system of lines being so arranged that each, as far as possible, will be at right angles to the probable direction of the various fathom lines which must be assumed to be parallel to the coast line.

Sounding consists not merely in obtaining sufficient soundings to fill in the blank spaces on the chart, but in so thoroughly searching the whole area under examination with the lead line as to make sure that the least depths have everywhere been satisfactorily and accurately ascertained. Unless the least depths are so ascertained actual rocks or shoals may be missed. In the case of plans of new anchorages or channels, the resulting chart, through giving a false sense of security and so inducing ships to use it that would otherwise have avoided the locality, may prove to be an even worse danger than having no chart at all.

The only method to ensure that the least depths are not missed is close sounding, and a further rigorous examination of the smallest indications of an irregularity in the bottom. By close sounding is meant not only that successive casts of the lead are obtained close together when running along each line, but also that the lines of soundings themselves are close together. How close, in order to ensure that irregularities are not missed, must to some extent depend on the depth and on the nature of the bottom. Off flat sandy shores a more evenly sloping bottom may be expected than off irregular or rocky shores, and therefore the lines of soundings may be spaced further apart in the former case than in the latter, with equal confidence of detecting irregularities.

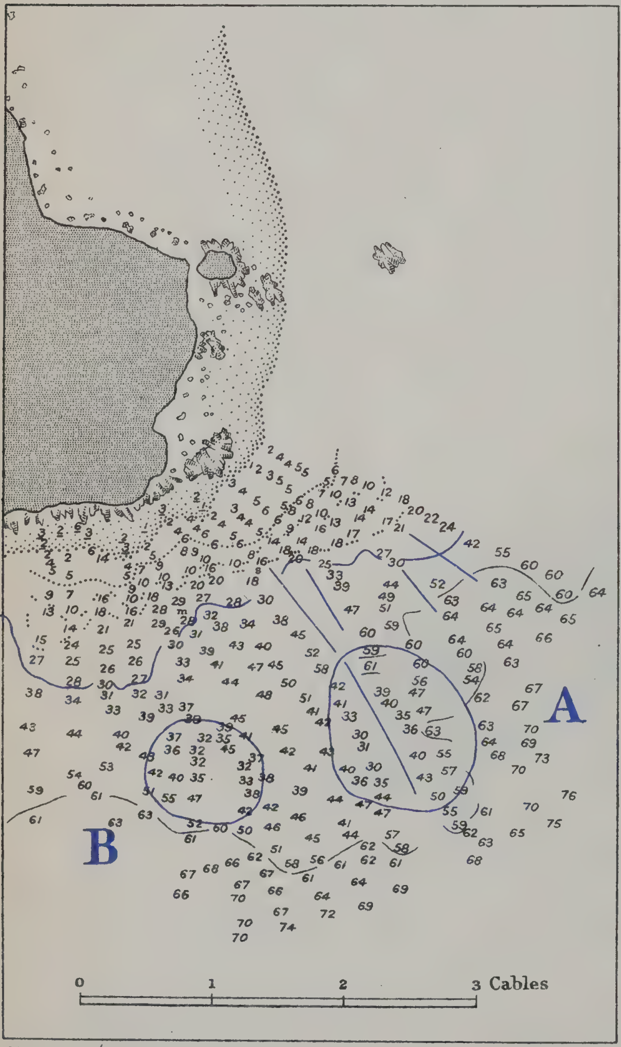
As a general rule lines of soundings should be run as close together as the scale of the survey permits. About five lines to the inch is as close as they can be plotted on paper without overcrowding. Therefore the scale (§ 4) should be sufficiently large to ensure that, with the lines at this distance apart on the paper, they may be sufficiently close in reality for a thorough examination according to the probable nature of the bottom. When the depths are over ten fathoms the distance between the lines of soundings may be increased.

With regard to the distance apart of successive soundings, the speed of the boat should be regulated so that sounding may be continuous without stopping, as long as the water is shallow enough to enable this to be done ; as the water deepens, the way of the boat should be checked as soon as the leadsman is ready, in order that he may get an up-and-down sounding. When necessary the way should be stopped altogether.

In shallow water many more soundings will generally be obtained and entered in the sounding book than can be legibly plotted, and a selection will have to be made, care being taken always to include the shallower casts. It is impossible to plot too many soundings on the field board provided they are legible, and none should be eliminated with the object of improving the appearance of the chart, this being the duty of those

I

Copy of a Sounding sheet showing original lines of soundings with 2 areas A & B and 4 lines, marked in blue, to indicate the re-examination required owing to irregularities in the depths.



3512. 38739/405. 12.500.1.15.

I

Copy of the sa
showing in red the a
obtained on re-exam
rocky danger with 2
A and one of 29 fee

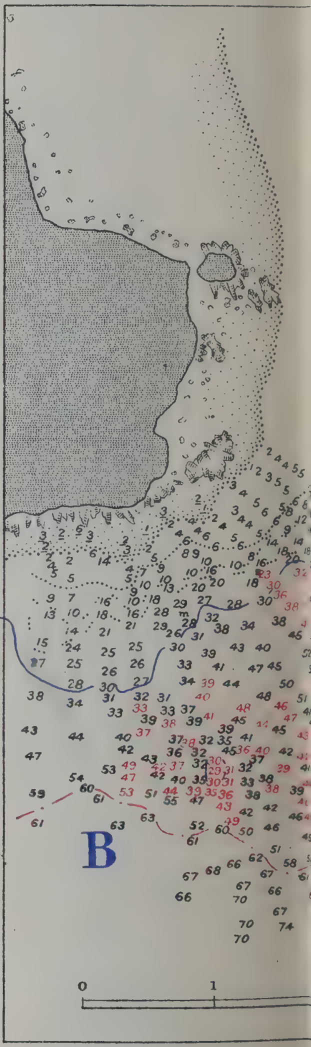
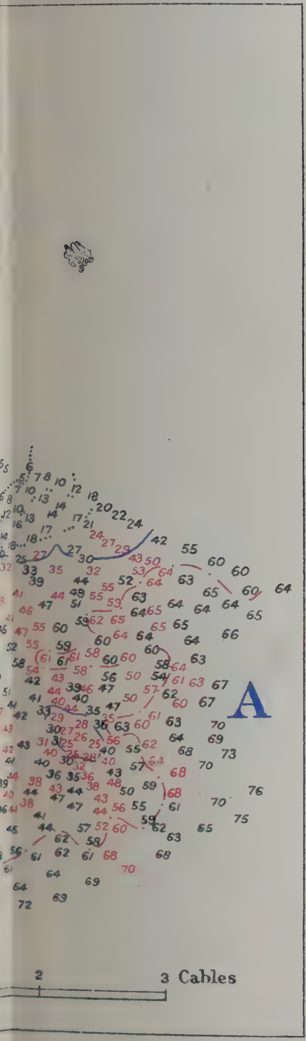


Fig.

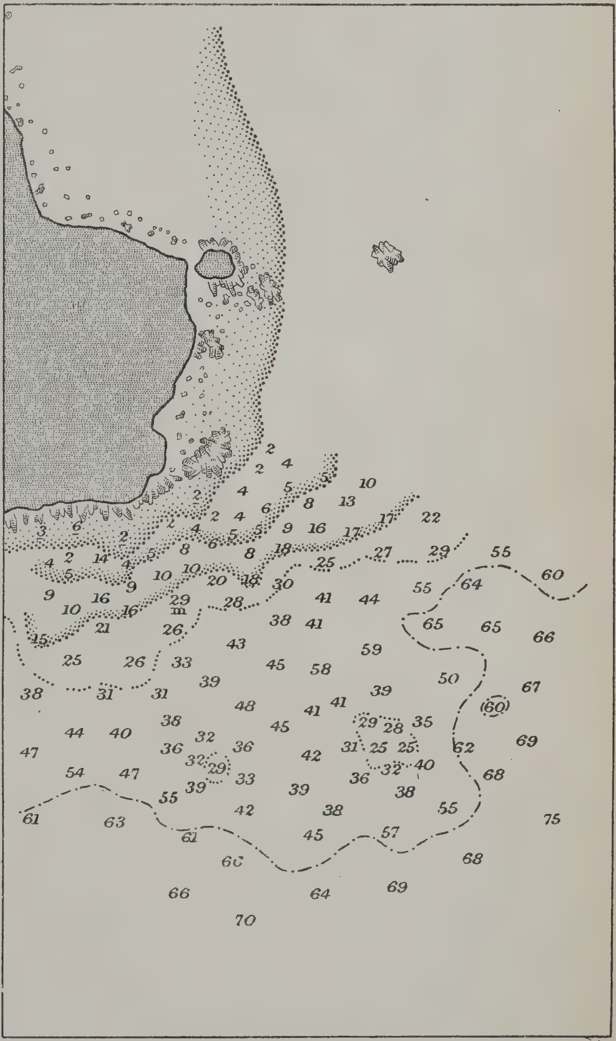
II

ame Sounding sheet
additional soundings
mination revealing a
25 feet least water at
et at B.



III

The same area as prepared in the Hydrographic Department for placing on the published Chart.



Malby & Sons, Lith.

g.8.

in the Hydrographic Department who prepare the work for the engraver.

As stated above, the directions of the lines of soundings should, as a rule, be at right angles to the coast line. Points of land or reefs are often prolonged under the water by a narrow shoal ridge or by isolated dangers; radiating lines should be run round such points and should be unusually close together, and be further supplemented by cross lines to ensure that no narrow tongue or ridge is missed. In particular, all rocky points which are likely to be rounded closely by a ship should receive such close examination.

Every portion of the work, as soon as the soundings have been reduced (App. C. § 8) and plotted, should be critically examined to see what irregularities, or indications of such, have so far been revealed. All suspicious areas, or individual soundings which differ considerably from those in the vicinity, should be marked for further examination by circling them with a blue pencil line. As a general rule suspicion should be aroused if the soundings decrease when proceeding from the shore, or if the soundings in any direction decrease and then increase again, both of which conditions indicate a rise of the bottom; all abnormal or sudden changes in the depths require explanation. Having marked all suspicious spots, these must be closely examined by running short lines in between the previous ones, and others at right angles to them; should a shoal cast be obtained a buoy should be immediately dropped, and a minute examination carried out round it to obtain the least depth. A barricoe with a line and sinker should be kept ready for this purpose.

The buoy may be "starred round" by running lines of soundings radiating from it as centre, or the area in the vicinity of it may be slowly drifted over by the boat, the leadsman holding the leadline and literally feeling every inch of the bottom in order to detect the summit of the obstruction. After having dropped the buoy and fixed it, further fixing is only necessary on obtaining a shoaler cast, and only the shoalest soundings are required to be inked in (*see* Fig. 8).

It must be borne in mind that, however closely a spot may appear on paper to have been sounded, yet the actual soundings may be quite far enough apart for a rock to exist undetected. On a scale of six inches to the mile a numeral figure occupies a space of nearly 25 yards, while the summit of a pinnacle rock may be only a foot or two in diameter. When sounding, a sharp look-out must be kept for any appearance of discoloured water which may indicate the presence of a shoal. Coral heads in particular may often be detected by the eye, and even in turbid waters, given calm weather and a tideway, rocks may often be detected by a ripple at the surface, particularly when the observer is at a considerable height. With a muddy bottom a deeper sounding than usual is often an indication of a pinnacle rock, owing to the scour round the base of the rock causing a depression.

It is scarcely necessary to say that accuracy is essential; lead lines should be marked when wet, and the marks invariably tested against measured distances immediately after returning on board. If an error is found to exist, the soundings in the sounding book must be amended accordingly, remembering that if the line is too long the soundings which have been recorded will be correspondingly too shoal, and *vice versâ.* The leadsman must be constantly watched to see that he calls the soundings correctly, and also that his line is invariably up and down. If there is any doubt as to the accuracy of a particular sounding called, the boat should be stopped and the matter cleared up on the spot; a false shoal sounding recorded may otherwise cause an enormous waste of time and trouble when subsequently attempting to verify it.

The marking usually adopted for lead lines is not sufficient for surveying purposes, and additional marks are required. The system of marking lead lines as adopted in H.M. surveying vessels is shown in Fig. 9, and may be followed with advantage.

7. Boat Sounding.—The lines of soundings it is decided to run should be ruled lightly on the field board, and the boat taken as near as possible to the end of a line where work is to be commenced. The position of the boat should be plotted by a station pointer fix and the boat moved until in the desired position, which should be maintained by dropping the lead on the bottom and keeping the boat vertically over it.

The direction of the line of soundings is then found as follows:—

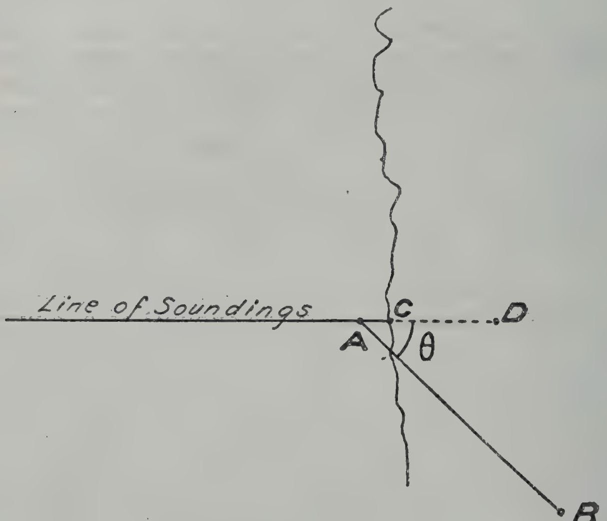
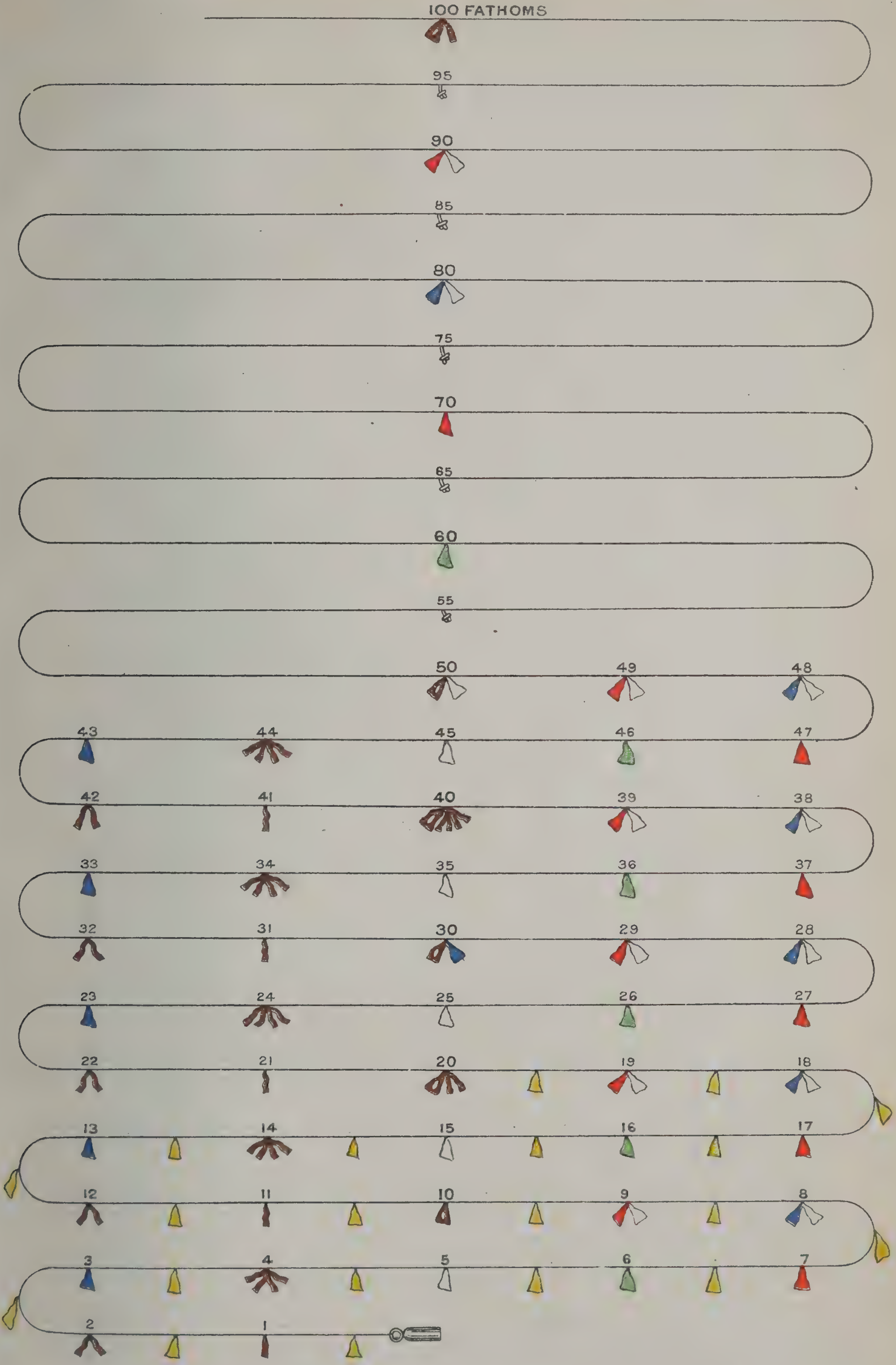


FIG. 10.

UNIFORM SYSTEM OF MARKING LEAD LINES



Lines (marked as above) to have in addition one knot inserted at every 1, 2, 4 and 5 feet of each fathom, for a sufficient length of line from the lead so as to ensure that at least 40 feet (reduced) may be measured at high water springs.
e.g. given springs rise 27 feet. 27+40 = 67 feet, therefore line to be marked in feet to 12 fathoms

3512. 38739/405. 12.500. 1.15.

Malby & Sons, Lith.

H.159

Fig. 9.

Let *A* (Fig. 10) be the position of a boat, *B* some point which has been plotted on the field board and θ the angle between *AB* and the first line of soundings. The observer having measured θ by means of the station pointer, places it on his sextant; he then, looking at the coast through the sextant telescope, finds that the object *B* is reflected to a rock *C* which is seen to be in transit with a tree *D*. In this case the rock and tree provide a leading mark which coincides with the required line of soundings. The boat is then moved along the line and soundings are continuously taken. The soundings should be called by the leadsman in fathoms and feet when the depth is less than 5 fathoms, and in fathoms and quarter-fathoms when the depths are between 5 and 20 fathoms. The position of the boat should be fixed at every few soundings, a check angle being taken occasionally and, if possible, at the extremities of each line. The fixes should be plotted and numbered consecutively, and the nature of the bottom noted at every fix. The entries are made in a book, called the sounding book, as shown below :—

No. of Fix.	Time.	Fix.	Sounding at Fix.
	H. M.		
1	10 20 A.M.	Beacon 38° 13′ Pier 62° 20′ Mill ,, 41° 30′ Bat 7¼ — 7 — 6 — 6 — 5½.	7½ m
2	10 25 A.M.	Beacon 42° 10′ Pier 65° 16′ Mill 28 — 28 — 27 — 26 — 26.	30 ft. r

Accuracy of fixing is equal in importance to accuracy of sounding; inaccuracy usually results not so much from actual errors in the observations as from making use of badly placed objects. When sounding it is a waste of time to read off the sextant to fractions of a minute of arc. The nearest 5 minutes of arc is a sufficient degree of accuracy provided the objects used are well selected, in which case an error of this amount should never appreciably alter the position of the fix. Two officers should be in each boat in order that the two angles of the fix may be observed simultaneously; one officer should enter the angles and soundings in the sounding book and plot the fixes as obtained, while the other "takes charge," watches the leadsman, &c. The larger the scale of the survey the more necessary it is that the angles should be observed simultaneously.

On account of tidal streams, currents, or imperfections in steering, it frequently happens that a fix shows that the boat is considerably off the correct line; in such a case the boat should be brought back to the line by the shortest route and another fix obtained. The track of the boat between successive fixes should be drawn on the field board.

8. The Tide Pole and Tidal Observations.—All soundings, before being plotted, require to be reduced to the same datum as that used for the published chart, or if no datum is given to the level of M.L.W.S., consequently it is necessary to obtain a continuous record of the heights of the level of the sea above the datum; this is done by means of a tide pole, a simple form of which is a plank graduated in feet and quarter feet as shown in Fig. 11. The tide pole should be set up in a well-sheltered spot where, if possible, it can be read from the shore. The water at the pole should not be so shallow as to leave the pole completely exposed at the lowest tide, and the pole should be of sufficient height to project above the water at the highest tide.

Whenever it can be done a mark should be made on some fixed object near the tide pole, so as to correspond with a particular graduation of the pole, in order that it may be possible to replace the pole exactly should it be accidently displaced.

The level of the water, as indicated by the tide pole, should be observed every half hour when sounding is being carried out, but about the times of high or low water it should be taken every 10 minutes. In order to find the reading of the tide pole which corresponds to the datum of the chart, one of the following methods must be used:—

(*a*) Where the published chart gives a connection between the datum and the top of a pier, or rock, &c., from which a vertical measurement to the water can be made. Add together this measurement and a simultaneous tide pole reading, and subtract the amount given as the connection on the chart. The remainder is the reading of the tide pole corresponding to the datum.

(*b*) Where the published chart gives no such connection but states that a rock in the vicinity dries a certain number of feet, then by noting the reading of the tide pole when the rock is awash, and from it subtracting the number of feet that the rock dries, the remainder is the reading of the tide pole corresponding to the level of M.L.W.S. The observation should be repeated with several different rocks and the mean accepted as correct.

(*c*) When neither of the above methods can be used, if the spring rise is given and the range of one tide is observed, then half the difference between the spring rise and the range of the tide observed, subtracted from the tide pole reading at low water, will give approximately the reading of the tide pole corresponding to the chart datum.

(*d*) When no tidal information is given on the chart the heights of high and low water on the tide pole should be observed, and the difference in height between the high water observed and the highest high-water mark shown on the shore line should be noted. (If

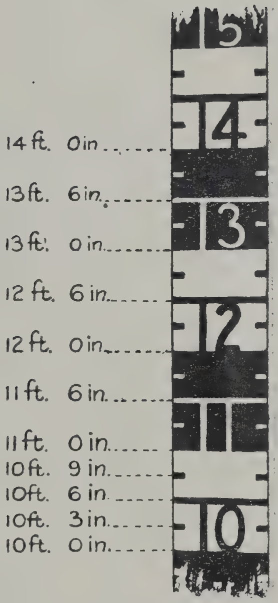

5
4
14 ft. 0 in.
13 ft. 6 in.
3
13 ft. 0 in.
12 ft. 6 in.
2
12 ft. 0 in.
11 ft. 6 in.
1
11 ft. 0 in.
10 ft. 9 in.
10 ft. 6 in.
10 ft. 3 in.
0
10 ft. 0 in.

FIG. 11.

this cannot be readily measured it may be obtained approximately by placing the eye at the high-water mark on the shore line in the vicinity and noting the reading where the horizon cuts the tide pole.) This difference, subtracted from the tide pole reading at the succeeding low water will give approximately the reading of the tide pole corresponding to the chart datum.

The values of the datum obtained by either of the two latter methods can only be regarded as approximate. Owing to the impossibility of judging exactly the height to which mean spring tides rise, the last may be seriously in error. If time permits, better values will be obtained if two consecutive tides are observed, and the mean of the results taken. When forwarding the work the fullest information should be given as to the method employed in obtaining the datum to which the soundings were reduced.

9. Placing the Soundings on the Field Board.—Before the soundings can be plotted on the field board, it is necessary to reduce them to what they would have been at M.L.W.S., or when the level of the sea was at the datum of the chart. This is done by comparisons with the readings of the tide pole at the times at which the soundings were taken; for example, suppose that the reading of the tide pole corresponding to the datum was found to be 5 ft. 4 ins., and that at 10^{h} a.m. and $10^{h}\ 30^{m}$ a.m. the readings were 9 ft. 8 ins. and 9 ft. 3 ins. respectively. Then the reductions at these times would be 4 ft. 4 ins. and 3 ft. 11 ins., respectively. The reduction for any intermediate time can be found from these two by interpolation. The reduced soundings should be entered in the sounding book in red ink underneath the observed soundings, and care should be taken that in reducing the soundings to quarter fathoms the smaller sounding is selected.

In the example given in §7, if the reduction is 4 ft. the reduced soundings would be entered in the sounding book in red ink as shown below by the figures in italics:—

No. of Fix.	Time.	Sounding.	Sounding at Fix.
1	H. M. 10 20 A.M.	Beacon 38° 13′ Pier 62° 20′ Mill - - „ 41 30 Bat - - 7¼ — 7 — 6 — 6 — 5½ *6½ — 6¼ — 5¼ — 5¼ — 4¾*	7½ m *6¾*
2	10 25 A.M.	Beacon 42° 10′ Pier 65° 16′ Mill - - 28 — 28 — 27 — 26 — 26 *4 — 4 — 3¾ — 3½ — 3½*	30 ft. r *4¼*

The soundings at the fixes should now be inked in on the field board, the intervening soundings being spaced between them. Should more soundings have been taken than can be conveniently plotted, the importance of the shallower soundings must be kept in view; for example, in the extract from the sounding book given above we have five soundings between the two fixes, and if there were only sufficient space for three soundings between these fixes on the field board, we should plot the centre sounding ($5\frac{1}{4}$) midway between the fixes and the shallower of the two soundings on either side of it. When all the soundings have been plotted the fathom lines should be drawn in, and if they show any marked discontinuity the area indicated should be closely examined.

10. The Collector Tracing.—As soon as the observations taken each day have been inked on the various field-boards, the work plotted on each board should be carefully traced on to a sheet of tracing paper. This tracing, called the collector tracing, will thus show at any time the whole of the work done up to that time. It will also show whether any gap is left between the areas examined by two officers, and whether their work exactly agrees.

On the completion of the work full information on every subject, giving the manner in which the scale and datum were obtained, the complete list of all observations taken, together with sounding books, field boards, plotting sheet, and collector tracing, should be forwarded to the Hydrographic Department where the necessary amendments to the existing charts will be made.

INDEX.

The numbers refer to the Articles.

- Advance 44
- Absolute altitude 146
- Absolute altitudes:
  - Comparisons for 147
  - Errors involved 148
  - Mean of results of A.M. and P.M. 148
  - Mean of results of stars, E. and W. 148
- Age of tide 234, 236, 239
  - To find 234
- Agulhas: Current 215
- Altitude:
  - Apparent 53
    - of heavenly body 103
  - Circles of 90
  - Correction of 108
  - Correction of supplement of 132
  - Formula for speed in 154
  - Maximum and minimum 127
  - Observed 103
  - True 53
    - of terrestrial object 53
  - True, of heavenly body 103
- Anchorage 159
- Anchoring:
  - in fog 179; 180
  - in selected position 182
  - Selecting position for 181
  - sounding round ship 181
- Anchors, Distance between 183
- Aneroid barometer, Description of 364
- Angle on bow 66
- "Anschütz" gyro compass, Description of 324
- Anti-cyclone 198, 201
- Anti-cyclonic winds 188
- Anti-lunar tides 224
- Anti-solar tide 228
- Apparent altitude of heavenly body 104
- Apparent time 94
  - Formula for 95
- Apogee 227, 231
- Aqueous vapour 186, 194, 196
  - Condensation of 194
- Arc, Conversion of to time 85
- Arctic current 213
- *Aries*, First point of 77
- Arming of lead 159, 361
- Artificial horizon. *See* Horizon.
- Asia, Change in pressure over, between summer and winter 187, 190
- Astronomical observations:
  - Method of working 116
  - Necessity for 68
- Astronomical refraction, Formula for 104
- Astronomical triangle, Formula for 101
- Astronomical triangle 90, 93
- Atlantic Ocean currents 213
- Atmosphere 186
  - Condition of 187
  - Humidity of 186
- Atmospheric electricity 196
- Attraction, Local 263
- Augmentation of moon's semi-diameter 107
- Aurora 196
- Australia, Winds round 190
- Azimuth 12
  - of heavenly body 91
  - diagram 102
  - tables 102
- Azimuth mirror:
  - Description of 301
  - To take bearings with 302

- Backing of wind 199
- Balance:
  - Time of oscillation of 346
  - Description of 345
  - Principle of 339
- Balance spring, Form of 345
- Barogram 211
  - Importance of shape of 211
  - Description of 365
  - Time adjustment of 211
- Barometer 187
  - Aneroid, Description of 364
  - Diurnal variation of 192, 207
  - Mercurial 363
  - Rate of fall of 211
- Barometer readings:
  - Correction for height 197
  - Correction for temperature 197
- Barometric gradient, Effect of motion of ship on 211
- Barometric gradients, To compare 188
- Bays, Indraught into 39, 171
- Bench mark 158, 161
- Binnacle, Description of 299
- Blink ice 221
- Bora 193
- Bottom, Nature of 159
- Bow, Angle on 66

The numbers refer to the Articles.

Bearing:
  Line of 48
  Lines of, Track to coincide with 173
  Magnetic 14
Bearing plate 303
Bearings:
  Selection of objects 62
  To take, with azimuth mirror 302
  True 12
  True, by observation 261
  True, from Mercator's chart 307
Belat 193
Below pole 125
Bench mark 158
Bergs 221
Beaufort's scale 188
Brazil current 213
Breakers, Sound of 179
British Islands:
  Tidal streams round 251
  Tides of 233
  Weather in 209
Buoyage system in United Kingdom 162
Buoys:
  Caution 162
  Distances between 180
Buys Ballot's Law 188

Cable 5
Cables, Strain on 182
Cancer, Tropic of 189
Capricorn, Tropic of 189
Celestial:
  concave 77
  equator 77
  meridians 78
  meridian of heavenly body 81
  meridian of observer 81
  poles 77
Centering error of sextant 332, 337
Centrifugal force, Effect on atmosphere 187
Centripetal forces due to moon 222
Chart:
  Scale of 115, 169
  Synoptic or synchronous 197
  To prepare 180
Charts:
  Abbreviations on 156, 157, 159, 160, 161, 163
  Correction of 168
  Co-tidal 233
  Datum of 232
  Defacing of 61
  Description of 168
  Distortion of, in printing 167
  Example of preparation of 184
  Fathom lines on 158
  Isobaric 187
  Mercator's 20
Charts:
  Necessity for 18
  of largest scale 170
  Printing of 167
  Reliability of 169
Chemical tube, Depth by 359
Chetwynd compass, Description of 297
China sea, Monsoons in 190
Chronometer 84
  box 353
  Error of 139
  Error of, by absolute altitudes 147
  Error of, by equal altitude 149, 152
  Error of, by time signal 142
  Description of 339
  Driving mechanism of 339, 340
  Greenwich test of 348
  journal 140
  Longitude by 130
  Notes on observations for error of 154
  Principle of 339
  room 353
  Rate of. *See* Rate.
  Safe distance from electrical instruments 351
  Stowage and care of 353
  Thermal compensation of 347
  To wind and start 352
  winding and maintaining mechanism 341
Circle of position 111
  on Mercator's chart 111, 123
Circumpolar 126
Clearing bearings 176
Clearing marks 175
Clocks, Adjustment of, for change of longitude 88
Clouds, Cause of 194
Coast charts not infallible 169
Coast line 156
Coasting, general rule 171, 179
Cocked hat 62, 117
Cod of storm 206
Coefficient *A* 313
  A′ 285
  B′, Correction of 279
  C′, Correction of 280
  D′, Correction of 281
  E′, Correction of 282
  J. 292
Coefficients, Approximate 277
  Exact 272, 278
  Relations between exact and approximate 276
Col 198, 205
Co-latitude 2
Collimation error 332, 335
Comparisons of chronometers 140, 147, 152, 153
Comparison, The mean 143

- Compass:
  - Approximate expression for the deviation of 274
  - between deck, To adjust 309
  - Card, Graduation of 13
  - Chetwynd, Description of 297
  - Component parts of deviation of 275
  - Deviation of 15, 270
  - Diagram 45, 46
  - Exact expression for deviation of 272
  - Expression for deviation of when ship heels 290
  - Gyro. *See* Gyro-compass.
  - in conning tower 304
  - Landing 259, 260, 261
  - Magnetic 13
  - Magnetic forces at 267
  - Magnetic, Suspension of 264
  - Observations for deviation of 306
  - Principle of correction of 271
  - Removal of bubble from 298
  - rose 23
  - Rules for adjustment of 308
  - Safe distance from electrical instruments 305
  - Sluggishness 304
  - Standard 15
  - Thomson, Description of 300
- Compensated balance, Description of 345
- Compensation, Thermal, of chronometer 347
- Composite track 37
- Concave. *See* Celestial.
- Conning the ship 185
  - tower, Compass in 304
- Constant parameters 267
- Constellations 70
- Contour lines 156
- Coral regions, caution 169
- Corrector magnets, Rules for placing 280
- Co-tidal charts 233
- Course 18
  - Formula for 28
  - made good 25
  - to allow for current 25
  - to be by Standard compass 185
  - to find by Mercator's chart 23
- Cross-bearings 62
- Currents:
  - Cause of 212
  - caution 169
  - Drift 212
  - of Atlantic ocean 213
  - of Indian ocean 215
  - of Pacific ocean 214
  - Set and drift of 25
  - Stream 212
  - To allow for when shaping course 25
  - To find 42
- Cyclone 198, 199, 206
  - Sequence of weather in 199
- Cyclonic winds 188

- Damping of gyroscope 318
- Danger angle:
  - Horizontal 178
  - Vertical 177
- Danger line, Limiting 169
- Dangers 157
  - Avoidance of, in thick weather 179
  - clearing marks or danger angles 180
  - Distance from 171
- Dangerous semi-circle 206
- Date 84
  - Change of, on 180th meridian 88
  - Greenwich 86
  - line 89
- Datum:
  - Height of tide from 242
  - Level of 158
  - of Admiralty charts 232
- Davis Strait current 213
- Day 82
  - Astronomical 84
  - Civil 84
  - Mean solar 84
  - Solar 83
- Dead-reckoning 38
- Deck watch 84
  - minute at last observation 132, 141, 154
  - To determine error of 140
  - To take time with 141
- Declination:
  - Correction of 87, 146
  - of heavenly body 78
  - Parallels of 78
  - Variation in 79
- Departure 26
  - Approximate formula for 29
  - conversion to *d*Long. 30
  - Formula for 27
- Depression:
  - Distance by angle of 59
  - of terrestrial object 54
- Depth:
  - by amount of wire out 360
  - by chemical tube 359
  - of water 158
- Derived tidal wave 233
- Deviation 270
  - Approximate expression for 274
  - Constant 275
  - Component parts of 275
  - Exact expression for 272
  - Necessity for observation of 311
  - Observations for determining 306
  - Quadrantal 275
  - Rules for applying 16

The numbers refer to the Articles.

Deviation:
  Semicircular 275
  Swinging ship for 310
Deviation table, Criteria of 312
Deviation tables 15
Dew:
  Causes of 194
  Point 194
Diagrams for plotting position lines 115
Diagrams, Tidal 243
Dip:
  Magnetic 258
  See Horizon.
Directions, Sailing 170
Directive force:
  Effect of permanent magnetism on 266
  of gyroscope 316
  of magnetic compass 264
Distance 18
  by great circle track 34
  Formula for 28
  of an object:
    by rangefinder 50
    by vertical angle 59, 60
  Shortest 18
  To find, by Mercator's chart 24
  to new course 44, 174
Diurnal inequality 226, 241
Diurnal tides:
  Lunar 226
  Solar 228
Diurnal variation of barometer 192
Doldrums 189
Dover, Tides of 233
Draught of ship 171
  in sea and river water 219
Drift currents 212

Earth:
  a gyrostat 314
  approximately a sphere 10
  Axis of 1
  Figure of 1
  Length of diameters 1
  Magnetic lines of force of 258
  Movement of 76
  Orbit of 73, 76
  Poles of 1
  Rotation of, effect on gyrostat 316
Ebb 232
Echo, Distance of cliff by 179
Ecliptic 77
Eddies 250
Electrical instruments' safe distance from compass 305
Electric current, Magnetic field of 256
Electricity, Atmospheric 196
Electromagnets 256
Elephanta 193
English Channel, Fog in 195
Epoch 155
Equal altitudes 146
  Comparisons for 152
  Equation of 149
  equation of, Formula for 150
  Errors involved in 151
  Error of chronometer by 149
  Longitude by 131
  Table for 131
Equation of time 95
  Correction of 98, 146
Equator 1
  Celestial 77
  Magnetic 258
Equatorial counter-current 213, 215
Equatorial current 213, 214, 215
Equilibrium theory 222
Equinoctial 77
  points 77
  spring tides 232
Error in position. *Se* Position.
Error of chronometer. *See* Chronometer.
Errors in absolute altitudes 148
Escapement 339, 344
Establishment:
  Mean, Correction of 235
  Mean, To find time of high water from 237
  Vulgar 238
Etesian 193
Ex-meridian altitude 128
Extraordinary spring tide 232

Fathom lines not drawn, caution 169
Field of magnet 252
Five fathoms line 169
Fix 61, 66
  Running 66
Fixing:
  by station pointer 65
  Necessity for 47
Flinders bar 279
  Induction in 294
  Quadrantal deviation due to 283
Floes 221
Flood 232
Fog 195
  Anchoring in 179, 180
  Navigation in 179
  Use of "stand by" observations in 132
Fog signals 164
  Reliability of 165
Force:
  Magnetic lines of 252
Forecasting the weather 211
Fort Dauphin 193
Foucault's law 315

The numbers refer to the Articles.

Four point bearing 66
Frigid zone 138
Frost, Hoar 194
Fusee 340

Geographical position of heavenly body 109, 110
Gnomonic chart 31, 32, 33
  Line of bearing on 48
Gnomonic projection, when used 167
Gradient, barometric 188
Gravity, Direction of 154
Great circle track:
  by gnomonic chart 31
  by calculation 35
  on Mercator's chart 34
  To find the course 34
  Towson's tables 36
Greenwich date 86
Greenwich:
  Royal Observatory 1
Gregale 193
Ground, Speed over 25
Guinea current 213
Gulder 233
Gulf stream 213
Gyro-compass 17
  Anschütz, Correction of 325
    Damping of 325
    Description of 324
    Receivers 326
  "Sperry," Correction of 322
    Damping of 322
    Description of 321
    Receivers 323
Gyroscope 314
  Damping of 318
  Effect of Earth's rotation on 316, 317
  Effect of rolling and pitching on 320
  Effect of ship's motion on 319
Gyrostat 314
  Effect of couple on 315

Hail, Cause of 194
Halo 209
Harbour rate 351
Harbours, Typhoon 208
Hard iron 255
Harmattan 193
Harmonic analysis of tides 242
Heavenly body:
  Geographical position of 109
  Position of 78, 103
Heeling:
  Coefficient 292
  Error, Changes in 296
Heeling:
  error, Constant 294
    Correction of, at sea 295
      in harbour 294
    Expression for 290
    instrument 293
    Necessity for correction of 295
Height of eye 132
Heights shown on charts 156
Helm:
  carried 185
  When to put, over 174
Helmsman, Orders for 185
High water, Time of 232, 237, 239, 240
H. W. F. & C. 238, 239
Hoar frost 194
Holding ground, Good 159
Hour angle 94
  Formula for 97
Horizon, Artificial 144, 145
  Dip of sea 55, 56, 103
  Dip of shore 58, 132
  Distance of sea 57, 163
  Distinctness of 132
  Hour angle of bodies on 133
  North, South, East and West points of 126
  Observations in artificial 146, 154
  Rational 103, 126
  Roof error of artificial 148
  Shore 55
  The observer's sea 55
  Uncertainty in position of sea 117
Horizontal angle, Determination of 261
  Use of, when anchoring 182
Horizontal danger angle 178
Horizontal force, Earth's 258, 265
Horizontal forces, at compass, when ship heels 268
Humidity 186
Hurricanes 206
Hydrometer 218
Hygrometer 186, 366
Hysteresis 255

Ice 221
Indian Ocean, Currents in 215
  Cyclones in 208
  South-West Monsoon in 190
Inequality, Diurnal 241
Index error 332, 336
  Determination of 132, 154
Indicator, Up and down 341
Indraught into bays 39, 171
Induced magnetism 255
  of ship 267
Induction in soft iron correctors 284

The numbers refer to the Articles.

- Instrumental error in absolute altitudes - 148
- Intercept - 112
- Invar - 347
- Illumination, Circle of - 138
- Intermediate course and distance - 44, 45, 46
- Iron, Hard and soft - 255
- Irradiation - 148, 154
- Isobar - 189
- Isobaric charts - 187
- Isobars, Fundamental forms of 198
  - over Asia - 187, 190
- Isochronism - 345
- Isotherms - 197

- Japan stream - 214

- Kaus - 193
- Kelp - 157
- Knot - 9
- Kuro Siwo - 214

- λ - 273, 286, 287
- λ_2 - 287
- Labrador current - 213
- Lagging of tide - 230, 235
- Laplace, Theory of - 74
- Latitude:
  - Angular - 2
  - by meridian altitude - 126
  - Difference of - 11
  - Linear - 8
  - Magnetic - 258
  - Middle - 29
- Lead, Arming of - 159, 361
- Leading marks - 172, 180
- *Libra*, First point of - 77
- Lightning - 196
  - Effect of, on deviation - 289
- Lights:
  - abbreviations on charts - 163
  - Height of, given on chart - 57
  - on buoys - 162
  - System of - 163
  - Visibility of - 57, 163
- Light vessels - 163
- Limb of body observed - 105, 154
- Line of bearing, Track to coincide with - 173
- Line of force of magnet - 252
- Line squall - 204
- Liverpool, Tides of - 233
- Local winds, Tabular summary of - 193
- Local attraction - 263
- Lodestone - 252
- Log:
  - Entries in ship's - 38
  - Patent - 354
- Longitude:
  - Angular - 2
  - by chronometer - 130
  - by equal altitude - 131
  - Difference of - 11
  - Linear - 8
- Look-outs in fog - 179
- Low water, Time of - 232
- Lubber's point - 15
- Lunar:
  - day - 230
  - tides - 224
- Lunitidal interval - 236

- μ, The meaning of - 291
- Magnet:
  - Artificial - 252, 256
  - Effect on isolated pole - 253
  - End on and broadside on - 253
  - Natural - 252
  - Poles of - 252
  - Strength of - 252
- Magnetic compass:
  - Directive force of - 264
  - Suspension of - 264
- Magnetic dip - 258
  - equator - 258
  - field - 252
  - field of electric current - 256
  - force - 258
  - induction - 255
  - latitude - 258
  - meridian - 258
  - poles - 252, 258
  - storms - 259
- Magnetic variation - 14
  - Changes in - 14, 259
  - Chart of - 14
  - Example of finding, on shore 262
  - Observations for, at sea - 313
  - Observations for, on shore - 260
  - Rules for applying - 16
- Magnetism - 252
  - Molecular theory of - 254
  - of earth - 252, 258
- Magnetism of ship:
  - Effect of sub-permanent - 288
  - Induced - 267
  - Permanent - 266
  - Sub-permanent - 269
- Magnetism, Red and blue - 252
- Magnets:
  - Effect of temperature on - 257
  - Rules for placing - 281
- Magnitudes of stars - 72
- Marine barometer - 363
- Maximum altitude - 127, 131
- Mean comparison - 143
- Mean establishment. *See* Establishment - 236
- Mean sun - 84
  - Motion of - 84
  - Right ascension of - 97, 99

The numbers refer to the Articles.

- M.T.P., Formula for - - 85
- Mercator's chart - - 20, 21, 22
  - Circle of position on - 111, 123
  - To find true bearing from - 307
  - where used - - - - 167
- Meridian altitude:
  - Position line by - - - 126
  - Time to take observation - 127
- Meridian:
  - Celestial - - - - 78
  - Circle of curvature of - - 3
  - Magnetic - - - 14, 258
- Meridian passages of heavenly bodies - - - - 125
- Meridian, Prime - - - 1
  - Right ascension of - - 96
- Meridional parts - - 20, 21
- Mexican current - - - 214
- Microphones - - - 166
- Middle:
  - latitude - - - - 29
  - temperature error - - 347
- Mile:
  - Geographical - - - 6
  - Length of - - - 5, 7
  - Nautical - - - - 4
  - Nautical, mean length of - 10
- Minimum altitude - - - 127
- Mistral - - - - - 193
- Mother tide - - - - 233
- Motion work - - - 339, 343
- Molecular theory - - - 254
- Monsoons - - - - 190
- Month - - - - - 80
- Moon - - - - - 73
  - Attraction of - - - 222
  - New and full - - - 229
- Moonset: Time of visible - 136
- Mooring:
  - line of anchors - - - 181
  - in selected position - - 183

- Nautical mile - - - - 4
  - Length of - - - - 5
  - Mean - - - - - 10
- Neap, Rise and range - - 232
- Neap tides - - - - 229
- Nebular theory - - - 74
- Nimbus cloud - - - 194
- North Atlantic, track recommended - - - - 221
- North Sea weather - - 209
- Note-book - - - - 180
- Notices to Mariners - - 168

- Objects, Selection of, in pilotage 180
- Observations, Best time to take 115, 132
- Observation spot - - 146, 154
- Ocean:
  - Temperature of - - - 220
  - waves - - - - 216
- Offing - - - - - 171
- Open marks - - - - 172
- Overfalls - - - - 250
- Oya Siwo - - - - 214

- Pacific Ocean currents - - 214
- Pampero - - - - 193
- Parallax - - - - - 106
  - Effect of, on tides - - 227
  - Horizontal - - - - 106
  - in altitude - - - - 103
    - Formula for - - - 106
  - sextant - - 327, 331, 336
- Parameters, Constant - - 267
- Patent log:
  - Description of - - - 354
  - Error of - - - - 356
  - Length of line for - - 354
- Pearl rock:
  - Clearing marks for - - 175
  - Horizontal danger angle for 178
- Perigee - - - - 227, 231
- Periodic winds - - - 190
- *Pelorus* - - - - - 303
- Permanent magnetism of ship 266
- Perpendicularity, Error of 332, 333
- Personal error in absolute altitude - - - - 148
- Peruvian current - - - 214
- Pilotage - - - - - 156
  - waters, Track of ship in - 171
- Planets - - - - 73, 105
- Polar distance - - - 78
- *Polaris*:
  - Azimuth of - - - - 129
  - Position line by - - - 129
  - Tables for - - - - 129
- Pole:
  - Altitude of - - - - 126
  - Elevated - - - - 77
- Poles:
  - Magnetic - - - - 252
  - of magnets - - - 252, 258
- Port, Establishment of. *See* Establishment.
- Position:
  - Area of - - - - - 117
  - by astronomical observation 115
  - by astronomical and terrestrial observations - - 124
  - by astronomical observation and sounding - - - 124
  - by bearing and angle - - 63
  - by bearing and distance - 64
  - by bearing and sounding - 67
  - by cross bearings - - 62
  - by dead reckoning - - 38
  - by horizontal angles - - 65

- Position:
  - by "Longitude by chronometer" 130
  - by plotting when altitudes very large 123
  - by soundings 67
  - Circle of 111
  - Error in—
    - due to error in altitude 117
    - due to errors in altitude and G.M.T. 119
    - due to error in G.M.T. 118, 140
    - due to error in the reckoning 120
    - due to errors in the reckoning and altitudes 121
    - due to errors in the reckoning, altitudes and G.M.T. 122
  - Estimated 39
    - Accuracy of 132
    - Unreliability of 47
  - Line 47
    - Astronomical 103, 112
    - by altitude of Polaris 129
    - by compass bearing 48
    - by distance 50
    - by ex-meridian altitude 128
    - by horizontal angle 49
    - by "Longitude by chronometer" 130
    - by meridian altitude 126
    - Notes on observations for 132
    - Track to coincide with 171
  - Most disadvantageous 117, 118, 140
  - Most probable 113, 117
  - triangle 90, 93
- Precession 315
- Pre-determined track, Turning ship on to 174
- Prediction of tides 236, 242
- Preparation of chart 180, 184
- Pressure:
  - Centre of high 187
  - Centre of low 187
  - of atmosphere 187
  - of atmosphere, Effect on tides 246
- Primary tidal wave 233
- Prime vertical 126
- Priming of tide 230, 235

- Quadrature, Moon in 229

- Race 250
- Radiation 201
- Rain:
  - Cause of 194
  - cloud 194
  - Non-isobaric 197
- R.A.M.S. 97, 100
- R.A * 79
- Range-finder, use of 50, 64
- Rate 139
  - Accumulated 139
  - Adjustment of 347
  - Change in, due to age 350
  - Daily 139
  - Effect of damp on 351
  - Effect of magnetic field on 351
  - Effect of ship's motion on 351
  - Effect of temperature on 347
  - Formula for 349
  - Observations for determining 155
  - of chronometer 155
  - Variations in 351
- Rational horizon 103
- Reciprocal bearings 306
- Reckoning 39
  - Accurate keeping of 132, 179
  - by calculation 41
  - by chart 40
  - by traverse table 41
  - during manœuvres 45, 46
  - in a tideway 43
- Refraction:
  - Abnormal 52, 56, 132, 148
  - Astronomical 103, 104
  - effect on visability 163
  - Terrestrial 51, 103
- Regulations for preventing collisions at sea, Article 25 180
- Revolutions of engines, Speed by 357
- Revolving storms 206
  - British Islands 209
  - Indications of approach of 207
  - Rules for avoiding 208
- Rhumb-line 18
  - Formulæ for 26
- Right ascension 79, 87, 97
  - of mean sun:
    - Change in 99
    - Correction of 100
  - of meridian 96
- Rising of heavenly body, Table of hour angles 133
- Roaring forties 189
- Rocks, Isolated 169
- Rocky shore 169
- Roof error, in absolute altitude 148
- Rounding a mark 174

- Safe distances:
  - Chronometers 351
  - Magnetic compass 305
- Sailing Directions 170
- St. Elmo's fire 196
- Sargasso Sea 213
- Satellites 73
- Scirocco 193
- Sea, Mean level of 232
- Sea rate 351
- Seasons 76

Sea water:
  Colour of 218
  Specific gravity of 218
Secondary cyclone 198, 200
Secular change in variation 259
Semi-circle, dangerous 206
Semi-diameter 103, 105
  Augmentation of moon's 107
Semi-diurnal tide:
  Lunar 226
  Solar 228
Sensitiveness of marks 172
Setting of heavenly bodies, Table of hour angles of 133
Sextant:
  Care of 338
  Description of 328
  Errors of 332
  Index error of 132, 154, 332, 336
  parallax 327, 328, 331, 336
  Principle of 327
  certificate 327, 332
  telescopes 330
  Vernier 329
Shade error 330
  in absolute altitudes 148
Shamal 193
Side error 154, 332, 334
Sidereal time 96
Signals, Storm 210
Single position line 113, 114
Soft iron correctors, Induction in 284
Solar day. *See* day.
Solar system 73
Solar tide 228
Solent, Tides of 233
Solstitial points 77
Sound waves 166, 179
Sounding book 361
Sounding machine 358, 361
Sounding without tubes 360
Soundings:
  How to take 361
  Intervals between 361
  Necessity for 39
  Plotting, on tracing paper 67
  Use of, in obtaining position 67, 124
Soundings on chart, Caution 169
Southern ocean, Tidal waves in 233
Specific gravity, Sea-water 218
Speed:
  by measured distance 355
  by revolutions of engines 357
  Loss of, whilst turning 44
  made good 25
  over ground 25
"Sperry" gyro-compass, description of 321
Spring rise 232
Spring tides 229, 232
Squalls 204
Standard clock 142
Standard ports 242
Standard time 89
Stand of tide 232
Star, globe or finder 137
Stars 69
  Designation of 71
  Identification of 132, 137
  Magnitudes of 72
  To recognise 75
Station pointer:
  Description of 362
  To test accuracy of 362
  Use of 65
Stern marks, steadying the ship on 172
Storms. *See* revolving storms.
Storm signals 210
Straight isobar 198, 203
Stream currents 212
Submarine bell 166
Sub-permanent magnetism, The effect of 288
Sun:
  Mock 209
  Rise, visible, Time of 134
  Set, visible, Time of 134
Survey, accuracy of 169
Swinging ship 310
Synoptic:
  chart 197
  system, of weather analysis 197

Telescope, sextant 154, 330
Temperature:
  effect on magnets 257
  effect on rate 347
  in vicinity of ice 221
  of atmosphere 187
  of ocean 220
  of sea 221, 366
  Zone 138
Ten fathom line, caution 169
Terrestrial magnetism 252, 258
Theodolite 261
Thermometer: 366
  Maximum 367
  Minimum 368
  wet and dry bulb 366
Thomson compass 300
Thunder 196
  storms 196, 200
Tidal:
  atlas 251
  constants 245
  diagrams 245
  streams 169, 247, 248, 249
    Rates of 169, 250
    round British Islands 257
Tide:
  Age of 234, 236, 239
  Height of composite 229
  day 230

- Tide:
  - generating forces 222, 228
  - Horizontal, generating forces 223
  - Lunar diurnal 226
    - semi-diurnal 226
  - Mother 233
  - prediction 236, 242
  - Priming and lagging of 230, 235
  - Range of 232
  - rips 250
  - Rise of 232
  - Single day 243
  - Solar diurnal 228
    - semi-diurnal 228
  - Spring, Cause of 229
  - Stand of 232
  - To find height of 243
  - wave, Primary and derived 233
  - waves 241
- Tides:
  - Abreviations for 160
  - British Islands 233
  - Composition of lunar and solar 229
  - Diurnal inequality of 241
  - Effect of atmospheric conditions on 246
    - of earth's rotation 225
    - of moon's declination on 226
    - of moon's parallax 227
    - of sun's parallax on 228
  - Equinoctial spring 232
  - Extraordinary spring 232
  - Harmonic analysis of 242
  - To find height of 244
  - Irregular 243
  - Lunar and anti-lunar 224
  - Neaps 229
  - of Solent 233
  - Solar and anti-solar 228
- Tideway, reckoning in 43
- Time:
  - Astronomical 84
  - Change of 85
  - Civil 84
  - Conversion of to arc 85
  - Equation of 95, 98
  - Mean solar 84
  - Sidereal 96
  - signal, Error of chronometer by 142
  - Standard 89
  - taking, for astronomical observations 141
- Tornado 193
- Towson's tables. *See* Great circle track.
- Tracing paper, use of 65, 67
- Track to coincide with position line 171
- Trade winds 189
- Train 339, 342
- Transfer 44
- Transit:
  - Deviation of compass by 306
  - Objects in 63, 172
  - of heavenly body 82
- Translation, Error of 294
- Travelling rate 351
- Traverse:
  - diagram 45, 46
  - table 30
- Triangle, Astronomical 90, 93
- Trident log, Description of 354
- Tropical storms, nuclei of 189
- Tropics 138, 189
- Trough of storm 206
- Turning, Track of ship while 44
- Twilight 135
  - Observations at 115, 132, 154
- Typhoon harbours 208
- Typhoons 206

- Variables of Cancer and Capricorn 189
- Variation. *See* Magnetic.
- V. depression 198, 204
- Veering of wind 199
- Venus, Orbit of 74
- Vernier, Principle of 329
- Vertical angle, Distance by 59
- Vertical danger angle 177
- Vertical force 258
- Views on charts 156
- Vigia 157
- Vulgar establishment. *See* Establishment.

- Water, Specific gravity and colour of 218
- Waterspouts, Cause of 194
- Waves:
  - Cause of 216
  - Height of 216, 217
  - Length of 216, 217
  - Period of 216, 217
- Weather 186
  - daily reports 209, 211
  - forecasting 211
  - round British Islands and North Sea 209
  - Variations in 197
- Wedge 198, 202
- Westerly winds 189
- "What Star is it?" *See* Stars, Identification of 137
- Williwaw 193
- Wind:
  - Cause of 188
  - Circulation of, about centre of high pressure 188
  - Cyclonic 188
  - effect on tides 246
  - Trades 189
  - Veering or backing 199

The numbers refer to the Articles.

Wind:
  Velocity and direction of - 188
Winds:
  Anti-cyclonic - - - 188
  Local - - - - - - 193
  Periodic - - - - - 190
  Permanent - - - - - 189
Wireless Telegraphy, time by - 142
Wreck marking vessel - - 162

Year - - - - - 76, 77, 80
  Mean solar - - - - - 84

Zenith - - - - 90, 103
Zenith distance - - - 92
  Calculated and true - - 103
  Calculation of - - - 101
  Very small - - - 111, 123

Zodiac - - - - - - 77

Zone:
  Frigid - - - - - - 138
  Temperate - - - - - 138
Zones, Tropical - - - 138

ML 1886.2

Phillips Library
3 6234 00116415 4